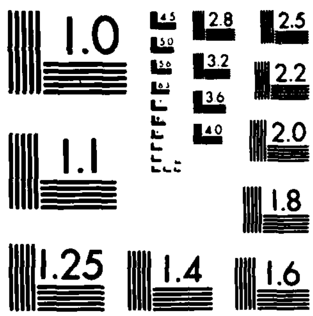

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Advanced Digital Controller Development Program, Task I

Detroit Diesel Allison
Division of General Motors Corporation
P.O. Box 894
Indianapolis, Indiana 46206

July 1982

Interim Report for Period 1 September 1979-30 September 1980

Approved for public release; distribution unlimited

Aero Propulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this program phase was to develop the specification for a digital controller. This controller would have sufficient computing and I/O capability to control a variable cycle (VCE) single spool (e.g. GMA 200 ATEGG) or two spool (e.g. GMA200 JTDE) configuration. Provision has been made for seven controlled variables. These are: two fuel flows, variable compressor and turbine geometry, two cooling bleed flows, and variable nozzle area. cont

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20. **ABSTRACT (Continued)**

cont

A multivariable control logic structure ~~has been~~ was selected. Power commands, mode, and ambient conditions are used to estimate the equilibrium operating point. These schedules will then be adjusted to match the engine characteristics using an adaptive control algorithm. "Optimal" paths between operating points will be computed by a "trajectory generator" module. A proportional regulator is designed to track small perturbation from this nominal path. Failure detection and accommodation will be provided by a fault tolerant filter, engine protection logic, and a failure accommodating actuator compensation module.

The design concept for a digital controller capable of implementing this control logic was developed. This required a specification of the GMA200 fuel control system with particular emphasis on the controller interface. Trade studies were identified and their impact on the control hardware presented. These included actuator selection, fuel system selection, and airflow measurement techniques. Timing and sizing studies were completed. This resulted in the selection of a bit-slice processor (an Am 2901) with 28K EPROM/RAM.

PREFACE

This report, prepared by the Detroit Diesel Allison (DDA) Division of General Motors, Indianapolis, Indiana 46206, documents technical effort accomplished during the Task I portion of Air Force Contract F33657-79-C-0728, "Advanced Digital Controller Development Program." This effort was sponsored by the Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, during the period September 1979 through September 1980. Mr. Les Small served as Air Force Project Engineer.

Dr. R. C. Boyer was the Project Manager at DDA. Other DDA personnel contributing to this program were Mr. J. H. McGrew and Mr. J. H. Hunter. The Bendix Energy Controls Division contingent consisted of project leader Mr. Frank O'Keefe with Mr. Art Kahlich. The Systems Control Technology (SCT) effort was completed by project leader Steve Rock.

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LIST OF ACRONYMS

A/D	analog to digital
ATEGG	advanced turbine engine gas generator
BLD	bleed
CDT	compressor discharge temperature
CIA	communications interface adapter
CPU	central processing unit
DDA	Detroit Diesel Allison
DMA	direct memory access
EEC	engine electronic control
EHSV	electro-hydraulic servo valve
EMC	electro-magnetic compatibility
EMI	electro-magnetic interference
EPROM	erasable permanent read only memory
FTF	fault tolerant filter
GE	General Electric
HPC	high-pressure compressor
HPT	high-pressure turbine
I/O	input/output
IRP	intermediate rated power
JTDE	joint technology demonstrator engine
LSI	large-scale integration
LVDT	linear variable differential transformer
MN	Mach number
ms	milliseconds
MVC	multivariable control
PLA	power lever angle
PMA	permanent magnet alternator
PROM	permanent read only memory
ROM	read only memory
RAM	random access memory
RPS	reference point schedule
RSS	root sum square
RVDT	rotary variable differential transformer
SCT	Systems Control Technology, Inc.
SFC	specific fuel consumption
TGEN	trajectory generator
TM	metal temperature
VCE	variable cycle engine
WF	fuel flow
WFA	primary fuel flow
WFB	main fuel flow

LIST OF SYMBOLS

Δ	incremental change
δ	
$\underline{x}$	state vector
$\underline{y}$	output vector
$\underline{u}$	control vector
$\underline{C}$	regulator gain matrix
$\underline{K}$	Kalman gain matrix
$\underline{F}$	engine model plant matrix
$\underline{G}$	engine model control matrix
$\underline{H}$	engine model output matrix
$\underline{D}$	engine model couple matrix
θ	ambient conditions
T	temperature
P	pressure
A	effective area
A8	exhaust nozzle area
W	flow
^	estimated quantity

<u>Subscripts</u>

TG	trajectory generator
C	control
RP	reference point
AC	actuator
S	sensor
b	base point

I. INTRODUCTION

The purpose of this program is the design and initial development of an advanced digital controller incorporating state-of-the-art microprocessors, modern digital input/output (I/O) interface technology, and adaptive fault-tolerant multivariable control logic. This controller will have the capability of full authority control for all DDA ATEGG/JTDE variable cycle engines (VCEs) envisioned for the early and mid 1980s.

THE GMA200/ATEGG

The GMA200/ATEGG is a single-spool, nonaugmented turbojet engine designed for supersonic advanced tactical fighter applications. Seven control variables are available:

- o primary fuel flow (WFA)
- o main fuel flow (WFB)
- o compressor variable geometry (HPC)
- o turbine variable geometry (HPT)
- o nozzle variable geometry (A8)
- o turbine blade cooling (BLD2)
- o aft cooling modulation (BLD1)

Primary (WFA) and main (WFB) fuel flows are the primary performance determining variables. The compressor and turbine variable geometry (HPC and HPT) is used to change core operation characteristics while exhaust nozzle area (A8) is used to obtain high thrust response rates and to control turbine downstream loading. Engine bleeds (BLD2 and BLD1) provide turbine blade cooling and aft section cooling, respectively.

A GMA200 ATEGG engine schematic is shown in Figure 1.

TOTAL PROGRAM PLAN

The effort described in this report covers Task I of a total planned program consisting of five tasks. The overall program is described here preceding the summary of the Task I achievements. The overall program is divided into five tasks, as shown in Figure 2. A three-member team consisting of DDA as prime contractor with Bendix Energy Controls Division and Systems Control Technology, Inc. (SCT), as subcontractors have worked closely during Task I and will continue this collaboration on all phases of this program to ensure maximum exchange of technology between the participants. The primary responsibilities for each participant are also shown on this chart.

The first task generates a GMA200 VCE control system specification. During this task sufficient trade studies would be performed to define and select interfaces between the digital controller and other control components. This is followed by a digital controller specification that satisfies the control system requirements. Finally, a control logic structure is developed.

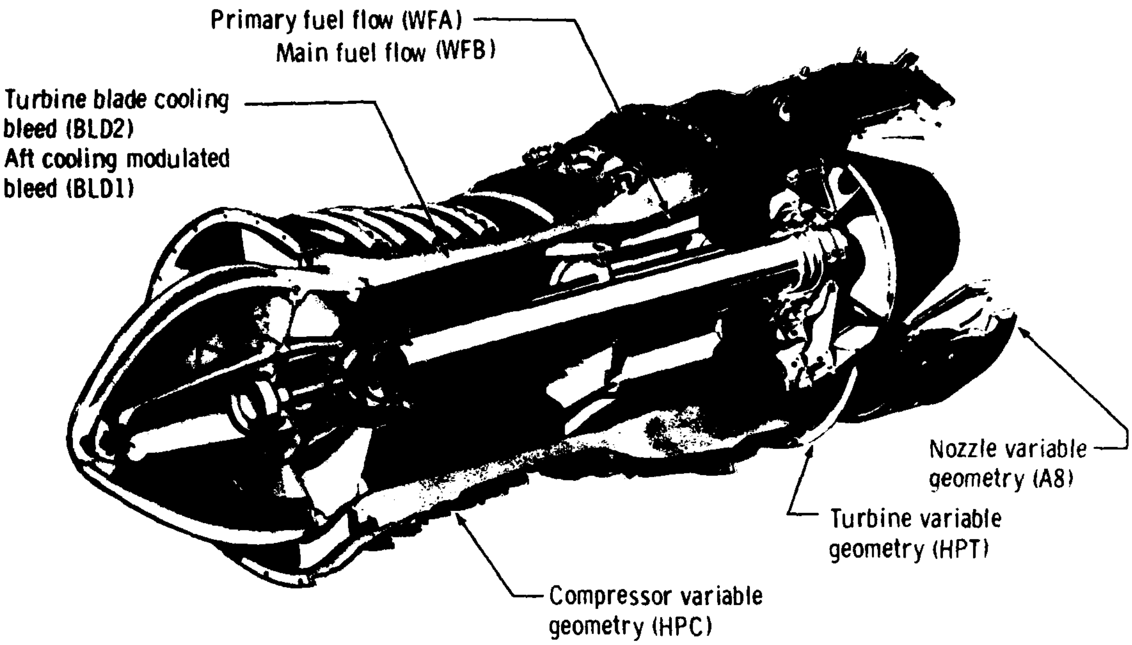


Figure 1. Schematic of the GMA200 ATEGG.

The control logic, based upon multivariable control design techniques developed by SCT, will be derived for the GMA200 ATEGG in Task II. The logic will contain a high degree of sensor and actuator fault accommodation. Adaptivity will be used to improve transient behavior. This task also includes the preparation of a software specification and software coding.

The digital controller hardware will be designed, fabricated, and environmentally tested in Task III. The basic processor will contain state-of-the-art technology and modern I/O interface technology. Two digital controllers will be fabricated. Existing test support equipment will be modified to support the new digital controller. One digital controller will be subjected to thermal cycling and vibration testing along with limited EMC and endurance testing.

During Task IV, a real time engine and control hardware hybrid simulation will be constructed with appropriate interfaces for the digital controller. The basic control logic and fault accommodation capability will be verified with the digital controller hardware, software, and the hybrid simulation. The digital controller will then be checked out on a fuel control bench test prior to running the engine.

Task V includes demonstrator engine testing. The first portion of the test will be conducted with the control only monitoring engine operation and all control loop closures external to the engine. Critical control functions will be checked during this phase of testing to ensure engine safety when the actual closed loop engine test with full authority digital control is authorized during the test.

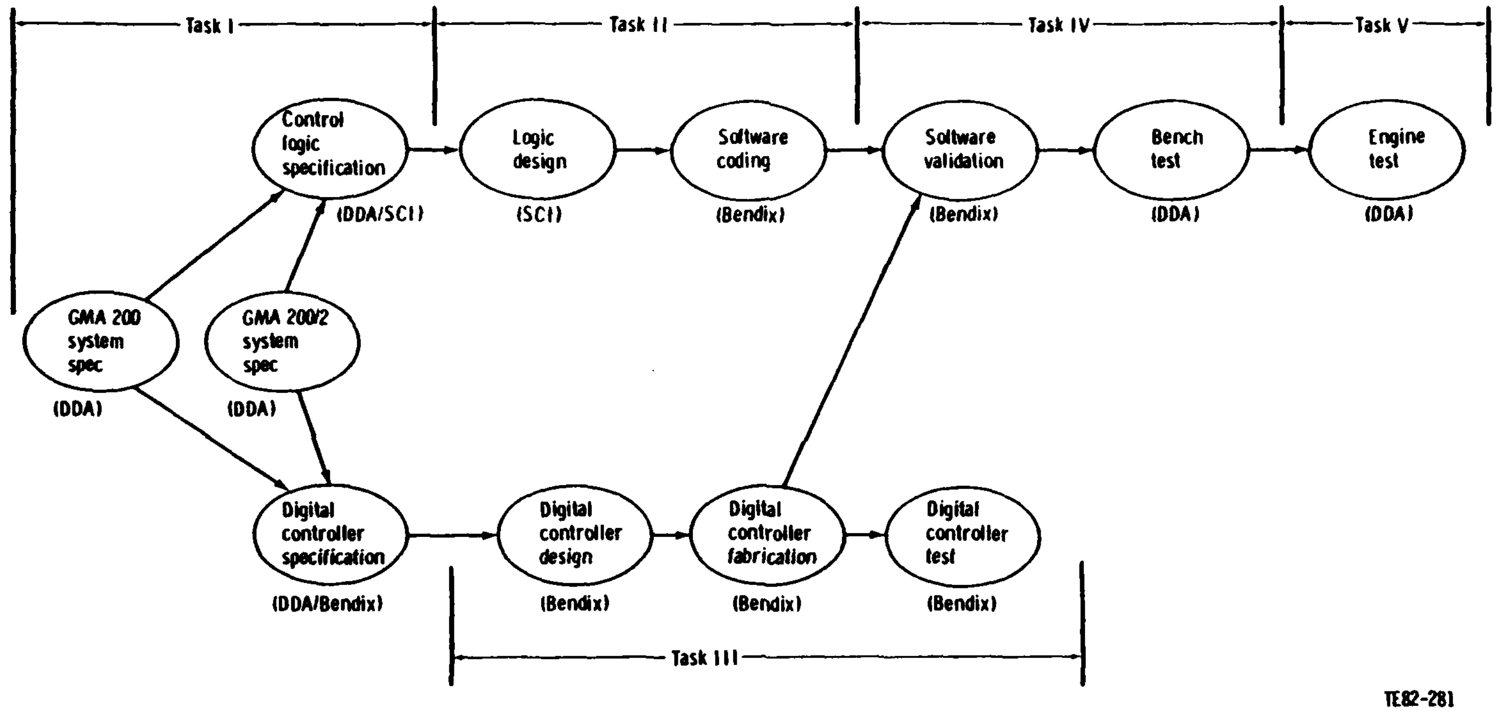


Figure 2. Program flow diagram.

TASK I PROGRAM

The objective of Task I was to generate a specification for a digital controller with sufficient capability to control the projected GMA200 VCE and ATEGG engines. To ensure a compatible digital controller, it was also necessary to generate system specifications for the projected engines with sufficient detail to identify system level performance and I/O requirements.

In support of these specifications the following studies were completed under Task I and are presented within this report:

Control Logic (Section II)

The multivariable control logic structure proposed by SCT is described. This includes such advanced concepts as fault accommodation, adaptivity, and "optimal" trajectory generation.

Microprocessor Trade Studies (Section III)

Trade studies were made between several microprocessor systems. These studies included microprocessor speed, power consumption, reliability, board sizing, and sourcing comparisons. Single processor, multiple processor, peripheral processor, and bit-slice processor approaches were considered.

Digital Controller Conceptual Design (Section IV)

A Bendix conceptual design of the digital controller was completed. This included a specification of the controller I/O capabilities, CPU selection, and a physical description of the control housing and associated modules (boards).

GMA200 Control System Specification (Section V)

The GMA200 VCE control system specification was developed with special emphasis placed on identifying sensor and actuator characteristics. This report describes the GMA200 system in its fully expanded configuration; that is, independent control of primary and main fuel systems, control of compressor and turbine variable geometry, control of exhaust nozzle area, and two cooling bleed flows.

Trade Studies (Section VI)

Trade studies were completed in several areas necessary to more accurately define the digital controller and its associated interface. These studies included the following:

- flow measurement accuracy
- backup control
- actuator feedback sensors
- torquemotor drivers
- fuel system configuration

II. CONTROL LOGIC STRUCTURE

The realization of improved engine performance and reliability goals relies heavily on the selection of a control algorithm. This algorithm must satisfy stringent engine limiting criteria and performance requirements in the presence of failures, disturbances, and engine degradation. A multivariable control was chosen as the desired control concept.

CONTROL LOGIC OVERVIEW

The control logic structure is shown in Figure 3. Reference point schedules are developed from pilot, mode, inlet, and ambient inputs. These points are "optimal" engine and control conditions for the desired thrust and current flight conditions. A "best" transition ($\underline{y}_{TG}$) between these desired "optimal" conditions and the current engine state is computed by a trajectory generator using feedback gains and an engine model. The multivariable control law generates control commands ($\underline{u}_c$) based upon current estimated engine parameters ($\hat{\underline{y}}$) and the desired engine control trajectory values ($\underline{y}_{TG}$). A fault tolerant filter provides this "best estimate" based on sensor readings and the engine model. Control parameters are adjusted in the engine protection monitor to prevent engine limit violations. An adaptive "outer loop" uses sensor outputs and predicted engine states to detect inaccuracies in the engine model. These inaccuracies are "corrected" by changing the reference point schedules.

The complex computations associated with multivariable control are matrix-oriented. The following definitions will apply:

- $\underline{x}$ is a state vector. It contains four states; these are rotor speed and three metal temperatures.
- $\underline{y}$ is the output vector. It contains system outputs (both measured and derived) and includes pressures, temperatures, flows, surge margin, and thrust.
- $\underline{u}$ is the control vector. It contains the control commands. These include fuel flow, bleed (cooling) commands, and variable turbine and nozzle geometry.

REFERENCE POINT SCHEDULES

Steady-State Solution

Reference point schedules (RPS) provide a prediction of the steady-state engine parameters ($\underline{x}_{RP}$, $\underline{y}_{RP}$, $\underline{u}_{RP}$) at the requested operating points. These schedules are computed using a static (steady-state) engine model.

The inputs to these schedules are PLA, mode, inlet commands, and ambient variables T1 and P1. PLA requests thrust continuously from idle to maximum power. Ambient variables determine the gas state at the engine inlet face.

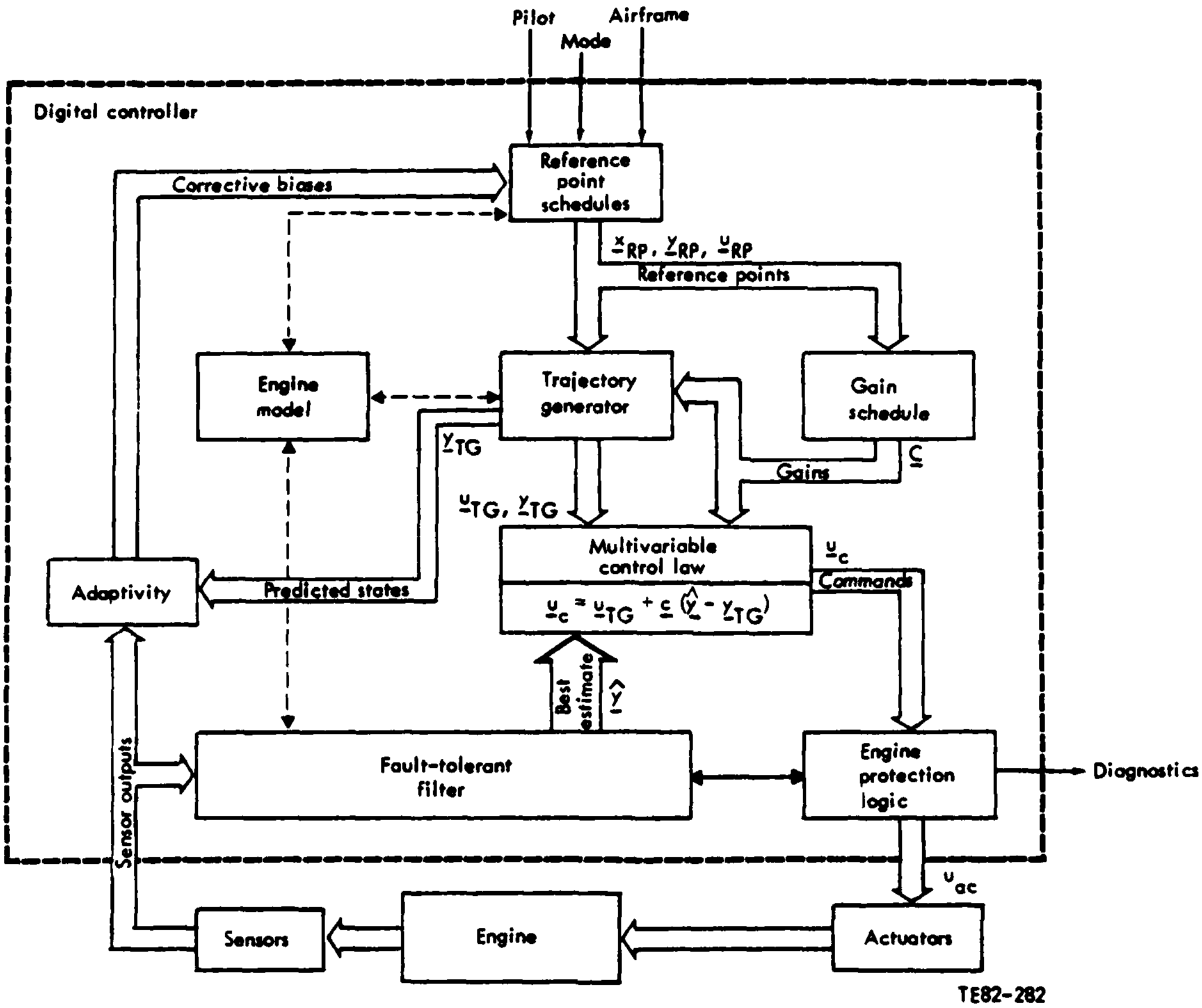


Figure 3. Control logic structure.

Mode Bias

The mode command is a means of moving the reference point schedules to satisfy specific operating conditions (e.g., minimum SFC mode, maximum thrust mode, increased stability mode, sensor failure, etc.). The memory required for tabular reference points to be scheduled at each mode is prohibitive. Thus, a scheme of "mode biasing" will be used. Here, mode "adjustments" ($\Delta\underline{x}$, $\Delta\underline{y}$, $\Delta\underline{u}$) are added to the reference schedules to generate the reference set points.

Reference Point Limiting

These new set points may violate physical or safety limits of the engine or control. Consequently, if limits are exceeded on the first pass, the reference schedules are recomputed with the over limit parameters fixed at their limits. This recomputation of reference schedules is done using a perturbation model of the engine.

Adaptivity

One additional adjustment is made to the reference schedules. This is a correction supplied by the adaptive control logic. The computation of this correction is discussed in a future section of this report.

TRAJECTORY GENERATOR (TRANSITION CONTROL)

The outputs of the reference point schedules will represent a group of engine variables and controls that satisfy equilibrium conditions and are within physical and operating limits. These quantities are based on the values of PLA, airframe, and inlet conditions. They can rapidly change from sample to sample because of pilot or airframe inputs. Consequently, the reference points can also change very rapidly and over a large range.

If these reference values were linked directly to the control, moderate engine transitions could saturate the actuators. Rate limiting of the reference points or the PLA commands would seriously degrade small signal response. Also, since the system response to very large inputs is nonlinear, the response achieved without some input compensation would be suboptimal (and most likely, catastrophic). The transition generator is designed to produce an ideal reference between the present engine state and the state most recently requested by the reference values.

The nominal reference trajectory should have the following attributes:

- be compatible with actual engine response (i.e., the reference input trajectory should nearly produce the reference output trajectories)
- nearly track all engine and actuator limits
- exhibit optimized response for both large and small inputs

The approach chosen for this function is to use a perturbation model of the engine as the generator of a "nominal" path.

The preliminary trajectory generation logic is shown in Figure 4. A nonlinear, proportional override logic is used as compensation. For small transients, reference point schedules are used as lagged commands to the engine model. The mode response is further compensated with gains that are equal to the optimal regulator gains. When no limits are exceeded by the model, the response of the model is controlled by the locally linear gains. When a model output approaches a limit, the servo rate limits are proportionally reduced. This has the effect of transferring the control law from the unlimited regulator to one of several specifically designed multivariable limit loops. The rate limit is proportional to the error signal from the limiting blocks. This feedback in one or more of the control channels will tend to cause the model to move smoothly onto a limit. If the proportional error signal indicates that the system can move away from the boundary, the limit is smoothly removed. The feedback gains for the limit loops are designed using output weightings on the specific engine constraints. This yields a feedback vector for the limit loop. This vector will be simplified using sensitivity calculation and scheduled as a function of ambient conditions.

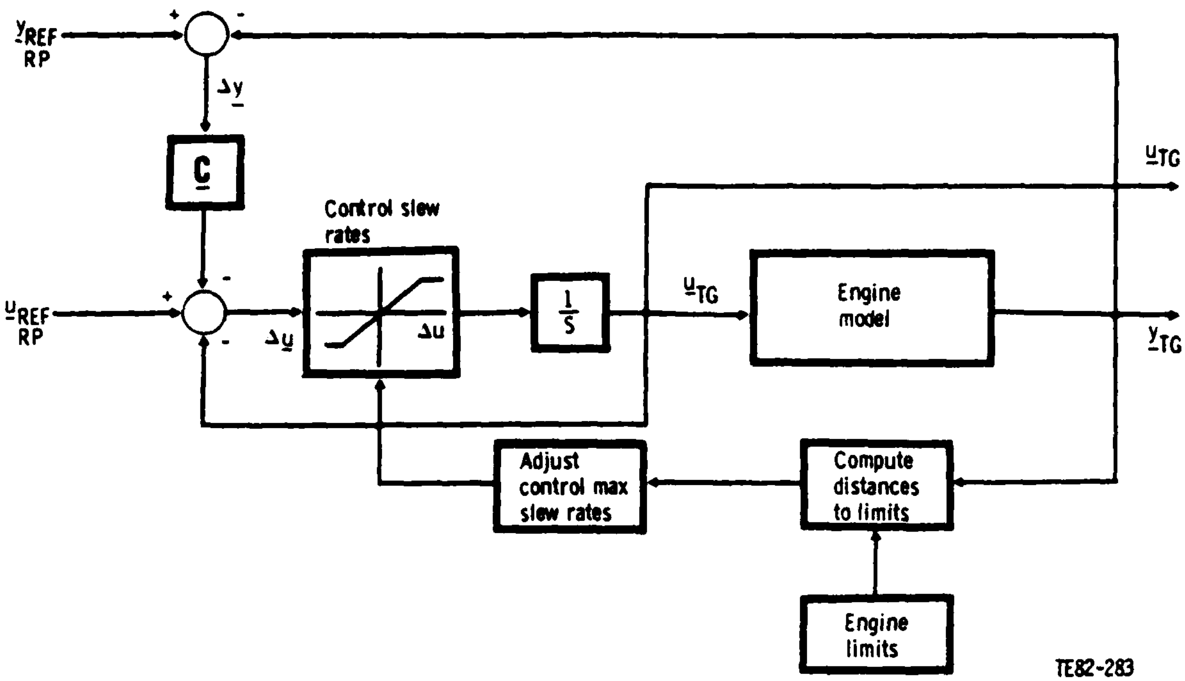


Figure 4. Trajectory generator schematic.

The large input performance of the system will tend to behave in a time-optimal fashion. This assertion is justified from optimal solution to the minimum-time problem for a linear system. Here, optimal trajectories consist of a minimum-time (corresponding to a bang-bang control) trajectory to a limit, tracking the limit, and moving off the limit to the final point. The character of the trajectories generated in this method will be very similar to this type of motion without the requirement of explicit solution of nonlinear optimization problems.

MULTIVARIABLE CONTROL LAW

The outputs of the trajectory generator are continuous control commands and engine variable references that predict the transition of the engine from one point to another without exceeding physical or operational limits.

If this prediction were exact or, alternately, if the mathematical model matched the engine exactly, there would be no reason to include a regulator. The regulator is designed to cause the engine to track small perturbations from a nominal trajectory. Further, it attempts to cause the engine to track the reference in steady state. The regulator will be a proportional control with set point accuracy and stability characteristics designed using linear optimal theory. Integral control will only be added as necessary. The form of the control will be

$$\underline{u}_c = \underline{u}_{TG} + \underline{C}\,(\hat{\underline{y}} - \underline{y}_{TG})$$

where $\hat{\underline{y}}$ is an estimation of engine operating states (the feedback) and $\underline{y}_{TG}$ is the trajectory generator output (the command).

Depending on the characteristics of the engine model and on the control design specifications, the regulator gains ($\underline{C}$) will either be designed for state variable feedback or output variable feedback. For either case, the resulting gains will be scheduled throughout the flight envelope. Low order polynomials based on the operating point variables will probably be employed.

ENGINE PROTECTION LOGIC

The outputs from the trajectory generator are held below their limits and used to produce nominal trajectories that track predicted engine response. Because of model inaccuracies, sensor and actuator lags and nonlinearities, build differences, etc., it is possible that actual engine limits may be exceeded transiently or in steady state. It is currently planned that no integral control will be used to compensate these types of errors. The engine limit logic provides additional d.c. gain to the system when limits are approached or slightly exceeded. This concept is shown in Figure 5.

As a limit is approached, a nonlinear factor is provided to the protection output gains specifically designed for this limit. As the exceedance increases, larger control effort is commanded. Above a certain value, it is concluded that the control logic is unable to produce safe regulation. At this point, an integrated over-limit-flag is passed to the error accommodation logic. The failed condition represents a nonspecific failure in the overall control function due to input failure, pilot error, actuator failure, engine component deterioration, engine auxiliary failure, or related causes. The control regards this as a NO-GO situation, and appropriate backup sequences are initiated.

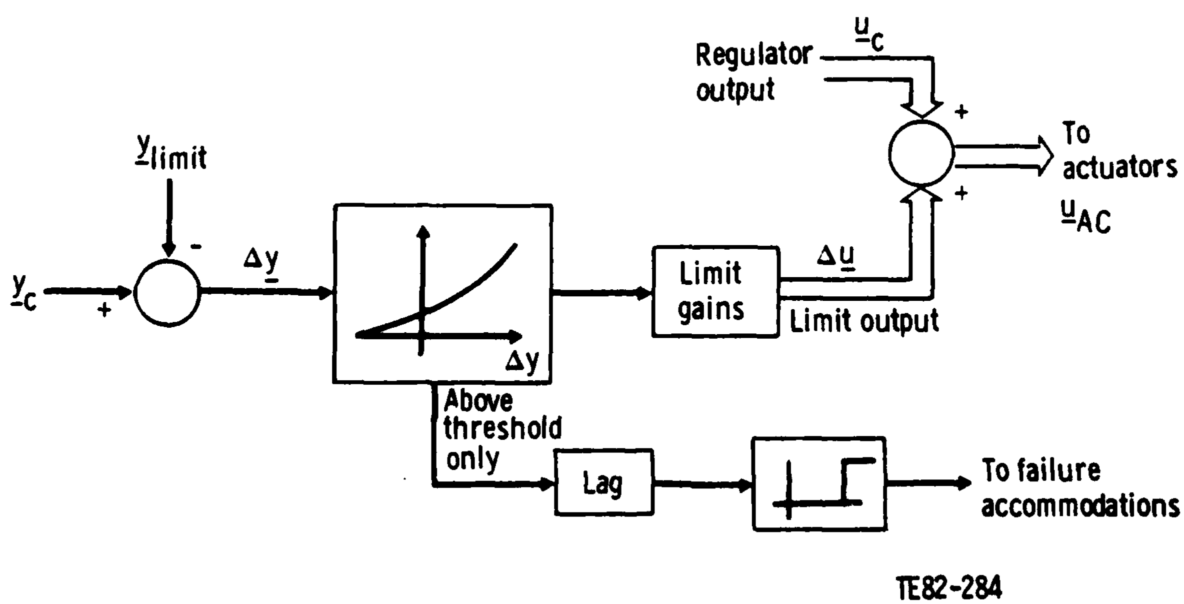


Figure 5. Engine protection logic.

FAULT TOLERANT FILTER

The signals entering the controller represent various types of discretized information. These signals provide many orders of redundancy concerning the actual measured quantities. The fault tolerant filter (FTF) provides the best available estimate of required information to the control law. It must operate on all analog sensor channels except PLA and inlet commands to provide the following:

- o noise attenuation
- o dynamic compensation
- o error correction
- o fault insensitivity

The filter uses a perturbation model of the engine in conjunction with an extended Kalman filter to provide dynamic compensation (lead). The form of a Kalman filter is

$$\dot{\hat{\underline{x}}} = f(\hat{\underline{x}},\underline{u}) + \underline{K}(\underline{y}_s-\hat{\underline{y}})$$
$$\hat{\underline{y}} = h(\hat{\underline{x}},\underline{u})$$

where $\underline{y}_s$ is the sensed signal matrix and $\hat{\underline{x}}$ and $\hat{\underline{y}}$ are estimated states and outputs, respectively.

The most important functions of the filter are to provide attenuation of errors due to various sensor noise sources, to compensate sensor dynamics that would otherwise compromise control performance, and to detect and accommodate sensor failures. Accurate d.c. response must not be degraded by the filter. The form chosen will be a series of decoupled extended or nonlinear Kalman filters with reduced gain matrices. The gains may be a function of the flight condition. The filter update will be provided by a nonlinear perturbation engine model. The design goals of this block will be high frequency noise rejection and d.c. accuracy. Foldover and aliasing due to sampling high frequency noise will be addressed by the design. Analog/digital prefiltering requirements, random sampling time algorithms, and adaptive noise rejection techniques will be investigated. A preliminary block diagram of the FTF is shown in Figure 6.

ENGINE MODEL

A key part of the control logic is a nonlinear model of the engine. Several of the functional logic blocks (e.g. trajectory generator, fault tolerant filter) use this model to obtain an accurate description of the dynamic and static behavior of the engine. Its structure will allow separate programming of steady-state and dynamic responses. The implementation of this model will be in a subroutine format so that various control blocks can use the same code with slightly different inputs and outputs.

Steady-State Model

The engine operating point is derived as a function of the inputs. Peripheral variables such as sensor output and nonscheduled actuator deflections are also predicted in this portion of the model. Nonmeasured outputs such as thrust,

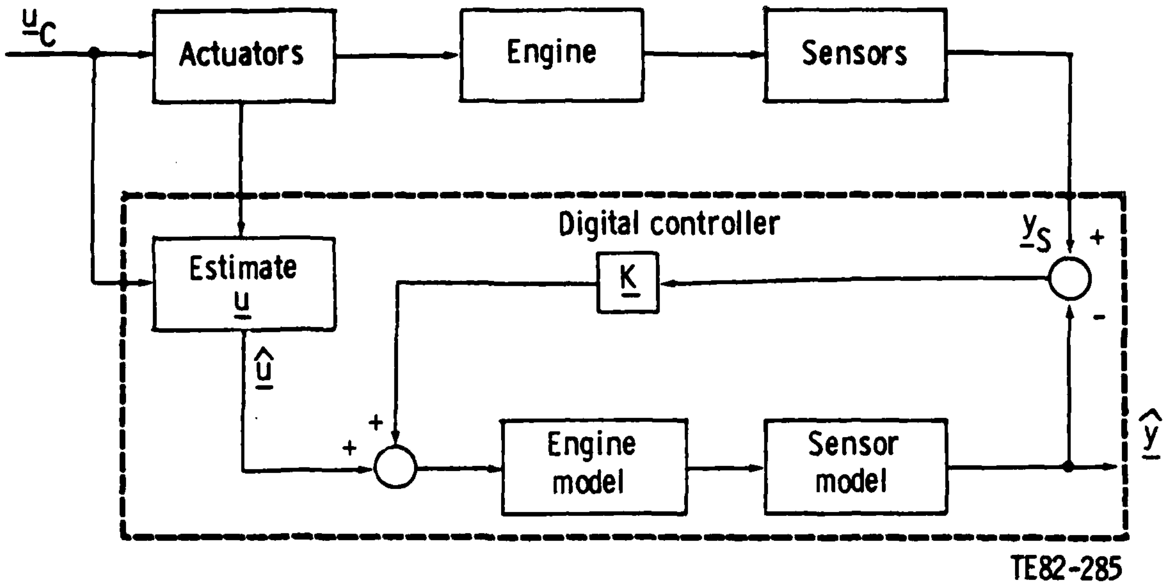


Figure 6. Fault tolerant filter block diagram.

stability margin, and airflows can also be approximated. The general form of the operating point function is

$$\underline{y} = h(\underline{x},\underline{u},\theta)$$

where $\underline{x}$ denotes the states; $\underline{u}$ denotes the controls; $\underline{y}$ is the estimate of all other states, outputs, measurements, and controls of interest at the desired point; and θ is the ambient condition. The function $h(\underline{x},\underline{u},\theta)$ will consist of tables or polynomial fits, depending on the most efficient implementation.

Perturbation Model

The dynamics of the engine will be constructed from reduced order linear models produced at various points in the flight envelope and mapped by a group of low order functions of auxiliary variables. These functions will most likely be implemented as polynomials of low order. Sensitivity methods will be used to reduce the problem to a manageable form. The model for the linear dynamics is

$$\dot{\underline{x}} = \underline{F}\,\Delta x + \underline{G}\,\Delta\,\underline{u}$$
$$\underline{y} = \underline{y}_b + \underline{H}\,\Delta\underline{x} + \underline{D}\,\Delta\,\underline{u}$$

where $\Delta\underline{x}$ and $\Delta\underline{u}$ represent perturbations from a reference (static) trajectory.

FAILURE DETECTION AND ACCOMMODATION

Sensor Failure Detection

A sensor failure detection algorithm will be associated with the fault tolerant filter. The purpose of this block will be to correlate filter residuals, sensed levels, and model outputs into references on soft and hard channel

failures. Multiple failures can be detected. This block will compare estimated gas path variables from the fault filter with the output of the engine model, y, as shown in Figure 7. A large differential or jump between the model and filtered data would indicate a hard failure and will be detected by the K_F term. An integrated time over a threshold value will be used to detect soft failures. It may be necessary to provide variable gains to achieve a robust system.

Sensor Failure Accommodation

In addition to the detection function, sensor failure accommodation will be provided. This will consist of manipulation of filter inputs to reduce the effects of bad sensor channels and optimize the integrity of the filter outputs. Also, logic indications will be passed to a central failure accommodation block for GO/NO-GO and secondary diagnostic processing.

Actuator Failures

Actuators are monitored for correct servo following. This system monitors error signal magnitudes compared with a threshold that is a function of the command level and changes in command levels. Threshold exceedance is considered as an actuator loop failure. The failure could be either the actuator or the feedback sensor. If the failure is in the feedback sensor, it is possible that the actuator could still be used to control the engine.

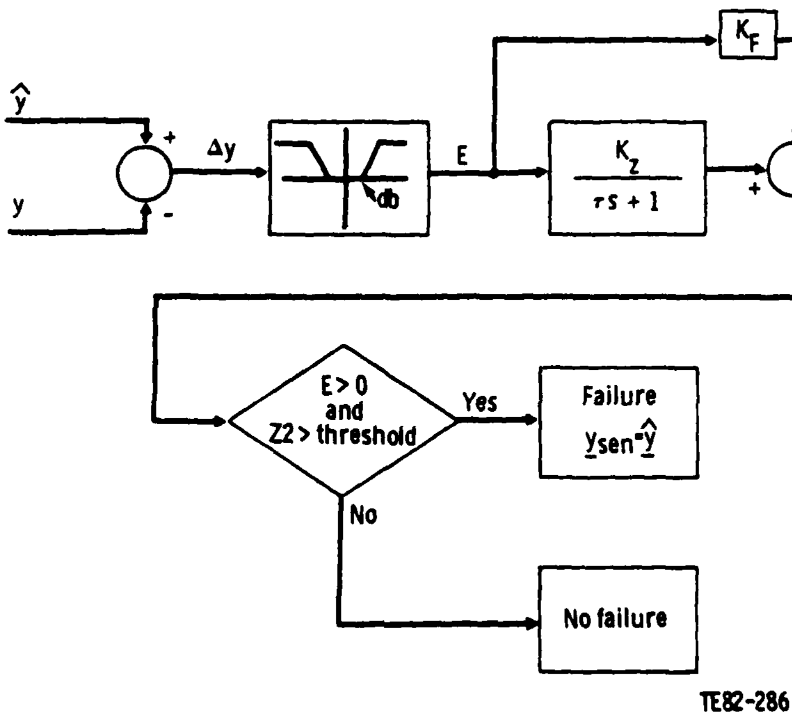


Figure 7. Fault detection schematic.

If the actuator loop is a closed loop on an engine parameter, the feedback sensor loop is primarily to make a tighter actuator control (reduce hysteresis and deadband), and the opening of the sensor loop would probably require a gain reduction (for stability) and the acceptance of a slower response. However, if the actuator loop is an open loop on engine parameters (scheduled geometry like the HPC loop), other logic will be investigated.

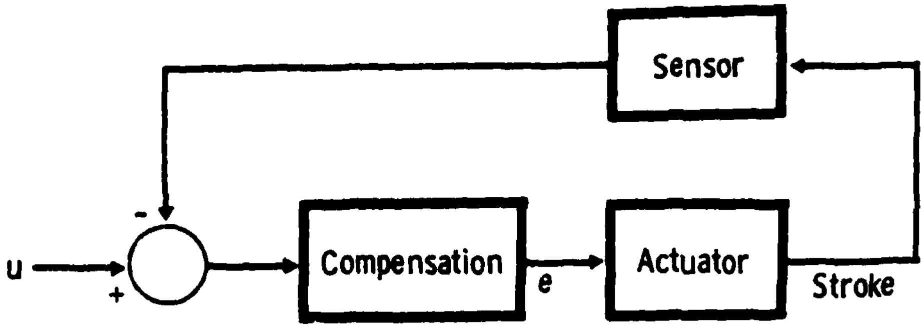
Normal operation is described in Figure 8a. Here the actuator is driven by an error signal (compensated) which is formed by comparing the actuator command with the feedback sensor output. In the event of a failed feedback sensor, the actuator can be driven by an estimate of the error signal, as indicated in Figure 8b. Here the error signal estimate is provided by an internal mathematical model of the actuator in the form of a subroutine. One common subroutine could be used to model all the servoloops in a computer storage efficient structure.

ADAPTIVITY

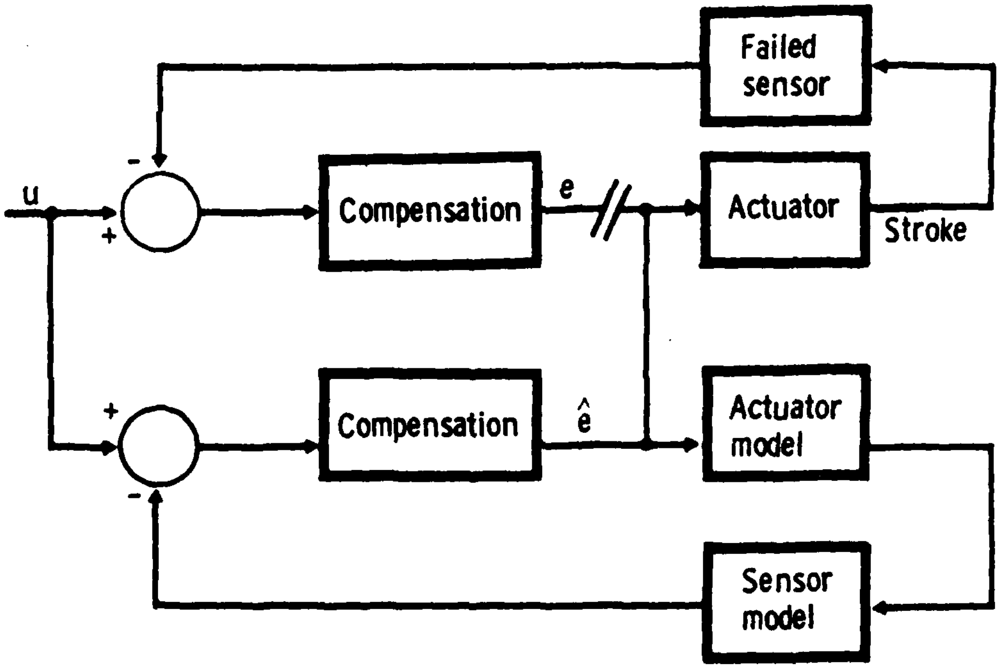
Adaptivity is an advanced concept that has significant potential for improving the transient response characteristics of the engine/control system. This is particularly true for a demonstrator engine control system in which the engine is likely to be significantly different from the engine models used to design the control logic. That is, adaptivity can offset performance degradation that results from modeling errors. These errors can result from build differences and/or engine deterioration. The principal disadvantage of adaptivity is the added computation that must be performed as part of the normal loop cycle.

There are two principal schemes of adaptivity applicable to the engine control problem. In the first, the control gains used in the multivariable control law are adjusted in response to changes in the engine's operating characteristics. In the second, the schedules are adjusted rather than the gains. The second technique has been chosen for this application. The reason is that steady-state hangoffs of the engine model away from the actual response introduce biases into the controls. These biases, and the modeling errors they represent, induce a larger effect on the transient response of the engine than a slight error in the feedback control gain. An alternate view is that (in a regulator designed for full envelope operation) the transient performance of the engine should not be overly sensitive to the feedback gains due to uncertainties in the model. Consequently, adjusting the reference point schedule to correct for modeling errors appears to be the most applicable strategy for adaptivity.

The function of adaptivity is straightforward. Its implementation is not necessarily so. Simply, engine performance is monitored and the reference point schedules adjusted on-line to match the performance. This can be accomplished in an outer loop that slowly adds a correction to the schedules until the hangoff is minimized. This correction can be in the form of a scale factor and bias. The correction parameters are calculated via a parameter identification algorithm (e.g., least-square fit). The problem arises in guaranteeing no impact on loop stability while minimizing the added computational complexity. Stability is an issue because adaptivity implemented in this form has some of the characteristics of integral control.



a. Normal Operation of Actuator Servo Loop



b. Operation of Actuator with Failed LVPT

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Figure 8. Actuator sensor failure accommodation.

A block diagram of the adaptive control logic is presented in Figure 9. The critical design parameters are the scheduled variables that will be modified by the adaptivity. They will include the most active controls (e.g., fuel flow and HPT geometry) and the noncritical outputs (e.g., P_3 and T_5).

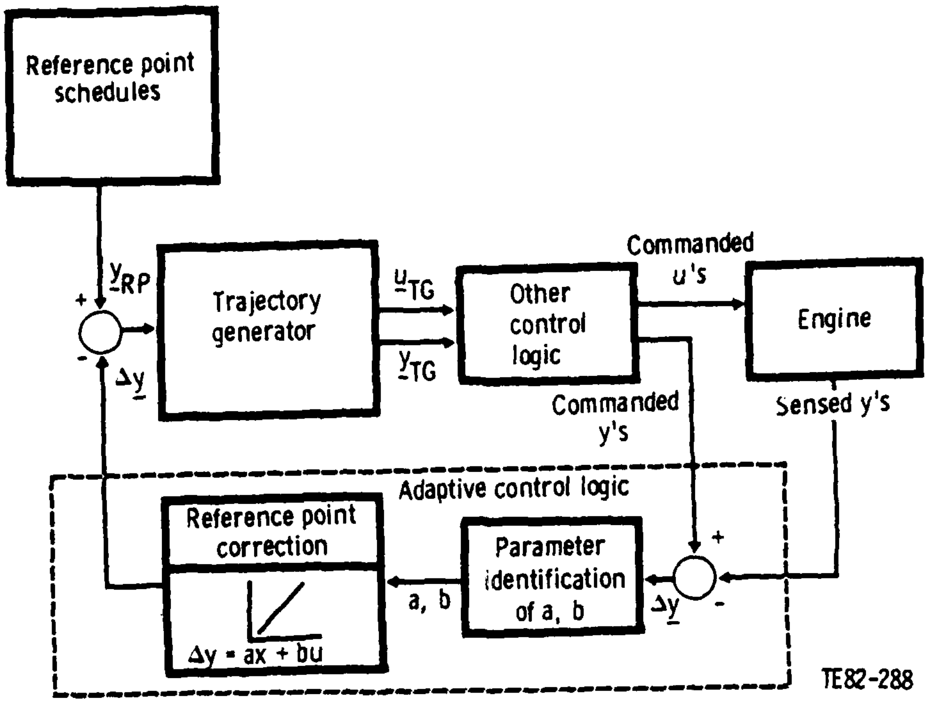

Figure 9. Adaptive control logic.

III. MICROPROCESSOR SELECTION CRITERION

SUMMARY

The following processors were investigated in detail:

- o SBP9900
- o SEL810B
- o Am2901B
- o SBP9900 + peripheral processor

The INTEL 8086, Z8000, and MOT 6800 were considered to be similar in characteristics to the 9900 microprocessor. The SEL810B is an example of a "fast" minicomputer used to implement the F100 multivariable control design tested by NASA Lewis Research Center in 1978.

Only the Am2901B (a bit-slice based processor) has a single processor approach with sufficient speed to execute the control logic. This processor uses bit-slice technology to emulate an existing (9900) microprocessor instruction set with special-purpose instructions to perform operations found in multivariable control applications.

Multiple microprocessor systems are another way to meet the computation speed requirements of the control law, but they have disadvantages. These systems are more complex to program, and when the level of multiprocessing exceeds three microprocessors, this approach requires more space and power and is heavier and more expensive than a single processor approach. This is due to the support devices, memory, and interconnection logic needed to make all of the microprocessors work together. The following timing study will show that, for example, the SBP9900 processor requires six levels of multiprocessing to equal the speed of the 2901B.

The 9900 microprocessor with a bit-slice peripheral processor provides a very significant improvement in speed over the SBP9900 but is complex in design and slower than the stand-alone bit-slice system. Its speed does not meet the desired computation rates.

The stand-alone bit-slice approach offers the highest reliability of all of the approaches that meet the processing speed requirements because the bit-slice processor system with memory uses fewer parts than a multimicroprocessor system and the number of gates per chip for the bit-slice system is closer to optimal for the highest reliability per gate. Another contributing factor to the high reliability of the bit-slice processor is its bipolar based technology, which has been proven to have higher reliability in military temperature range applications.

The bit-slice processor also offers clear advantages in size and availability. Its single disadvantage is a higher power consumption than the multiple microprocessor based system. This is countered by a signficant reduction in memory system power.

TIMING

An analysis was performed by SCT to estimate the distribution of operations performed within each of the functional logic blocks. The results are expressed in Table 1. Note that the control logic will be implemented in a multirate/multiloop architecture and that these have iteration rates of 50 Hz (20 ms) and 16.7 Hz (60 ms). Adaptive logic (which was not included in the following timing study) will be implemented in the slow (60 ms) loop. The 50 Hz (20 ms) "fast loop" update rate was required to ensure a 5 Hz control band width. Past experiece on JTDE/ATEGG (EH-K1) has shown this to be sufficient.

Table 2 presents the assumed operation times for three microprocessor configurations. A fourth configuration--the SBP9900 and peripheral processor--was not included in this table. For this configuration polynomial operations would be performed by a peripheral processor of the same speed as the 2901-based processor while the remaining operations are performed by an SBP9900.

The times given for the SBP9900 are actual times computed from code used in previous projects. SEL810B data were taken from instruction timing while the 2901-based 9900 times are estimated design goals based upon current knowledge of the 2901 and dynamic random access memory (RAM) cycle times.

Table 3 combines the estimated distribution of operations and operation timing to yield the computation time per loop. This may, in turn, be used to generate the net time required per 20 ms interval:

$$\begin{pmatrix} \text{Net time} \\ \text{per} \\ \text{20 ms interval} \end{pmatrix} = \begin{pmatrix} \text{20 ms loop} \\ \text{time} \end{pmatrix} + \frac{1}{3} \begin{pmatrix} \text{60 ms loop} \\ \text{time} \end{pmatrix}$$

or

o SBP9900	108.21 ms
o SEL810B	20.74 ms
o SBP9900 + pp	24.29 ms
o 2901-based 9900	7.83 ms

Note that only the 2901-based 9900 is capable of performing the control logic load within the allocated 20 ms period. The SBP9900, for example, would require over 100 ms to execute the computations desired in a 20 ms interval. This would imply at least six multiprocessor levels.

SIZING

The program memory requirements were determined by comparison with similar engine control logic developed by SCT. In particular, the F100 multivariable control is functionally similar to GMA200 and is also modular in structure. This comparison indicated that 16K memory was adequate for basic logic implementation. However, expansion capability for diagnostics, fault accommodation, redundancy management, and test stand requirements would be very limited. Consequently, a 28K memory size was selected to accommodate logic growth.

Table 1.
Distribution of operations.

FUNCTION	I/O	UNIVARIATE FUNCTION LOOK-UPS	BIVARIATE FUNCTION LOOK-UPS	POLYNOMIAL EVALUATIONS	LOGICAL IFS, ANDS, COMPARES	(MATRIX) ADD, SUBTRACT OPERATIONS	(MATRIX) MULTIPLY OPERATIONS	MISC. ARITH =, ADD, SUB. OPERATIONS	MISC. MULTIPLY OPERATIONS	MISC. DIVIDE OPERATIONS
INPUT (FROM PILOT)										
20ms Loop	6				6			2		2
SENSOR										
20ms Loop	14	10	4							
60ms Loop										
FTF (FAULT TOLERANT FILTER)										
20ms Loop		10	4		140	142	80	14	42	
60ms Loop		15	21	85	200	200	150	50		
RPS (REFERENCE POINT SCHEDULE)										
20ms Loop										
60ms Loop		16	25	10	50			78	26	26
TGEN (TRAJECTORY GENERATOR)										
20ms Loop					125	223	120	70	20	17
60ms Loop		10	15	85			20	10		10
MVC										
20ms Loop						41	20			
60ms Loop		10	10							
PROT (ENGINE PROTECTION LOGIC)										
20ms Loop		6	6		5	27	20	10		5
60ms Loop		5	5		10			30	10	10
ACOMP (ACTUATOR CLOSURES)										
20ms Loop	14	21			31	49	20	151	77	
TOTALS										
20ms Loop	34	47	14	0	307	482	260	247	139	24
60ms Loop	0	56	76	180	260	200	170	168	36	46

Table 2.
Execution times per operation.

Operation	Execution time in microseconds SBP9900	SEL810B	2901-based 9900
I/O	25.0	3.0	3.2
1-D table lookup	351.0	76.0	13.6
2-D table lookup	854.0	181.0	37.2
3rd order poly	223.0	18.0	12.8
Compare operation	11.0	3.0	2.4
Matrix add, sub	10.0	4.5	1.2
Matrix multiply	49.0	6.0	3.8
Misc arithmetic	10.0	3.0	2.4
Misc multiply	42.0	4.5	5.6
Misc divide	69.0	8.25	5.6

Table 3.
Loop execution times.

	Execution time in milliseconds							
	SDP 9900		SEL810B		SBP9900 & PP		2901-based 9900	
Operation	20 ms loop	60 ms loop	20 ms loop	60 ms loop	20 ms loop	60 ms loop	20 ms loop	60 ms loop
I/O	0.85	0	0.10	0	0.85	0	0.11	0
1-D table lookup	16.50	19.66	3.57	4.26	1.41	1.68	0.64	0.76
2-D table lookup	11.96	64.90	2.53	13.76	0.62	3.39	0.52	2.83
3rd order poly	0	40.14	0	3.24	0	3.64	0	2.30
Compare oper	3.38	2.86	0.92	0.78	3.38	2.86	0.74	0.62
Matrix add, sub	4.82	2.0	2.17	0.90	0.69	0.29	0.58	0.24
Matrix multiply	12.74	8.33	1.56	1.02	1.14	0.74	0.99	0.65
Misc arithmetic	2.47	1.68	0.74	0.50	2.47	1.68	0.59	0.40
Misc multiply	5.84	1.51	0.63	0.16	5.84	1.51	0.78	0.20
Misc divide	1.52	3.31	0.18	0.40	1.52	3.31	0.12	0.27
Totals	60.08	144.39	12.40	25.02	17.92	19.10	5.07	8.27

OTHER CONSIDERATIONS

Reliability Comparison

These failure rates were computed using the procedures of MIL-HDBK-217C assuming an airborne transport uninhabited environment, an average ambient temperature of 45°C, a learning factor of one, and a parts quality factor of 10:

Processor	Failures per million hr
6-SBP9900s	144.9
2901-based 9900 processor	30.3

Note the considerable advantage of the 2901 over the six level 9900 configuration required to perform the same logic.

Physical Size Comparison

The PC board sizing used assumes 39.5 in.^{2} of usable component area. It is evident from the table below that the 2901 processor is desirable from a board sizing standpoint.

Processor	Number of PC boards
6-SBP9900s	6
SBP9900 and peripheral processor	3
2901-based 9900	2

Processor Power Consumption Comparison

Estimated power consumption is as follows:

Processor	CPU power	Memory power	Total
6-SBP9900s	12.9 W	26.4 W	39.3 W
SBP9900 and peripheral proc.	18.3	8.8	27.1
2901-based 9900	17.0	5.0	22.0

Note that the 2901 processor is somewhat "power hungry." However this is countered by a savings in memory system power over multiple level systems.

Parts Sourcing Comparison

The SBP9900 is available from a single source--Texas Instrument. In contrast, the 2900 series is available from multiple sources including AMD, National, and Signetics. The advantage of multiple sources is clearly held by the 2901 processor.

IV. DIGITAL CONTROLLER CONCEPTUAL DESIGN

The heart of the engine control system is the digital controller designated as the EH-K2 by Bendix Energy Controls Division. This controller will be designed to control a DDA ATEGG/JTDE variable cycle engine using the multivariable control logic described in the previous section of this report. A microprocessor having sufficient speed to perform this logic will be selected and appropriate I/O transducers identified.

DESIGN REQUIREMENTS

The digital controller will receive information from the aircraft data systems, engine sensors, and control sensors. It will compute specified control logic and issue commands to the fuel system, variable geometry, cooling systems, and other special systems. In addition, the controller will monitor its own condition and have the capability of switching to a back-up control mode when a failure is detected.

Aircraft Inputs

The digital controller will communicate with the following aircraft digital controllers via dual redundant MIL-STD-1553B serial links.

- o air data computer
- o flight control computer
- o inlet controller
- o engine diagnostic computer

Pilot commands such as PLA and mode selection will be received by the digital controller on this bus. Display information for the pilot will also be transmitted on this data link.

Sensors Inputs

The digital controller will receive analog sensor signals, provide the required signal conditioning, and convert the signal to digital form (signal conditioning can be accomplished with the analog and/or digital signals).

Temperature. Four temperature to electrical analog signal transducers (thermocouples) will be external to the digital controller. The digital controller will provide amplification, signal conditioning, and analog-to-digital conversion of the thermocouple output.

The digital controller will receive a d.c. analog signal from the optical pyrometer electronics.

Pressures. The digital controller will provide the pneumatic pressure transducer, signal conditioning, and analog-to-digital conversion (if required) for the system absolute and differential pneumatic pressures. Three absolute and one differential sensor are required.

Speed. The digital controller will provide signal conditioning and analog-to-digital conversion (if required) for two speed signals from magnetic pickups.

Control Feedback. The digital controller will provide the excitation, signal conditioning, and analog-to-digital conversion for the following types of position transducers:

- o resolvers (8)
- o linear variable differential transformers (LVDTs) (2)
- o potentiometers (6)

Actuator Drivers

The digital controller will provide continuous modulated power to the following actuators:

- o fuel system
- o compressor actuation system
- o turbine actuation system
- o nozzle actuation system
- o aft actuation system

Solenoid Drivers

The digital controller will provide power to energize the following system solenoids:

- o start
- o de-ice
- o BLD1 vane cooling modulation (4)
- o fuel cutoff (2)

Discretes

The digital controller will receive discrete information for the following systems:

- o exciter
- o BLD1 pressure feedback (4)
- o test stand operations

Power

The controller will be capable of operating on Permanent Magnet Alternator (PMA) a.c. power or 28 VDC aircraft power.

Optical Data Bus

The digital controller will be able to transmit and receive control data to and from an identical digital controller over an optical data bus.

Self Check

The digital controller will provide the following hardware and software checks to determine a controller failure:

- o watch dog timer
- o wrap-around
- o memory sum-check
- o range and rate checks

The controller will issue the appropriate commands upon detecting a digital controller failure.

The computer will incorporate hardware alarms to detect loss of program control and malfunctions in the timing system.

COMPUTER ARCHITECTURE

Microprocessor and Memory

The control logic requirements of such advanced control logic as fault accommodation, adaptivity, and "optimal" trajectory generation result in a computational burden that cannot be efficiently handled with current hardware (e.g., the Bendix TI9900 based EH-L2). Consequently, Bendix has begun the development of an advanced controller (EH-K2) based on an Am2901B bit-slice processor tailored to multivariable control law execution. This processor will use bit-slice technology to emulate an existing microprocessor instruction set with some special-purpose instructions included to perform operations found in multivariable control laws. Timing studies leading to this choice were included in the microprocessor trade study portion (Section III) of this report.

A logic sizing study indicated that 28K of EPROM-RAM would be required to support the multivariable control logic and its associated fault accommodation, diagnostic capability, and redundancy management. Power switching circuitry is employed to remove power from these PROMs when they are not being accessed.

I/O Capability

Each EH-K2 controller will have the following capabilities:

- o four thermocouple channels, cold junction compensated
- o two speed sensor channels, variable frequency
- o four pressure sensors, three absolute and one differential
- o six analog input buffers
- o one potentiometer excitation driver
- o eight resolver conditioning channels
- o one resolver excitation circuit
- o two LVDT or RVDT conditioning channels
- o one LVDT or RVDT excitation circuit
- o six discrete input channels
- o seven torque motor driver channels
  - 3 ea $\pm$ 10 ma
  - 1 $\pm$ 20 ma
  - 1 $\pm$ 120 ma
  - 2 ea + 500, -250 ma
- o eight solenoid drivers
- o five relay drivers
- o one communications interface compatible with MIL-STD-1553B

These I/O channels will be allocated as shown in Table 4.

Table 4.
Controller I/O.

Controller output		Controller input	
T/M (7)	1. WFA	Temperature (4)	1. T1
	2. WFB		2. T3
	3. HPC		3. T5
	4. A8		4. TM
	5. BLD2		
	6. HPT	LVDT (2)	1. HPC
	7. Spare		2. Spare
Solenoids (8)	1. WFA C/O	Resolver (8)	1. WFA
	2. WFB C/O		2. WFB
	3. Air start		3. HPT
	4.		4. A8
	5. BLD1		5. BLD2
	6.		6. Spare
	7.		7. Spare
	8. De-ice		8. Spare
Relays (5)		Pressure (4)	1. PT1
			2. PT3
			3. PT5
			4. (PT1-PS1)
		Speed (2)	1. N
			2. N
		Discrete (6)	1.
			2. BLD1
			3.
			4.
			5. Initialization
			6. Spare
		DC (6)	1. Pyrometer
			2-6. Potentiometers

MODULE DESCRIPTION

The EH-K2 will be 5.2 in. high by 12.22 in. wide by 14.22 in. long. Its weight is estimated to be 30 lb. Figure 10 shows the proposed controller assembly.

The controller will consist of 13 modules. These include five CPU wire board modules, four pressure transducer modules, a thermocouple cold junction reference module, a power converter module, a communications interface adapter, and an interconnect harness. Figure 11 identifies the proposed system partitioning at a module (board) level.

Each module is briefly described below.

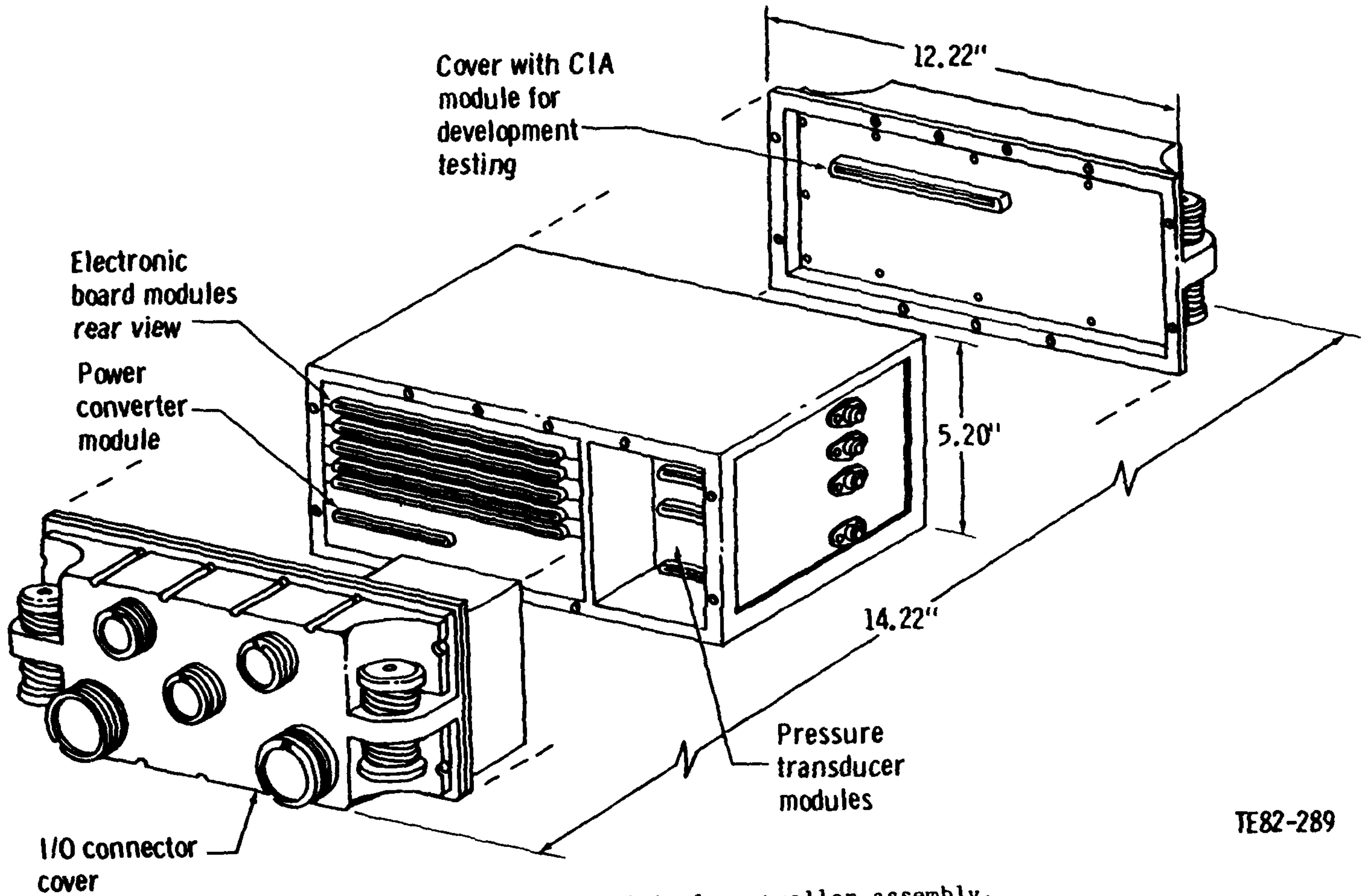

Figure 10. EH-K2 digital controller assembly.

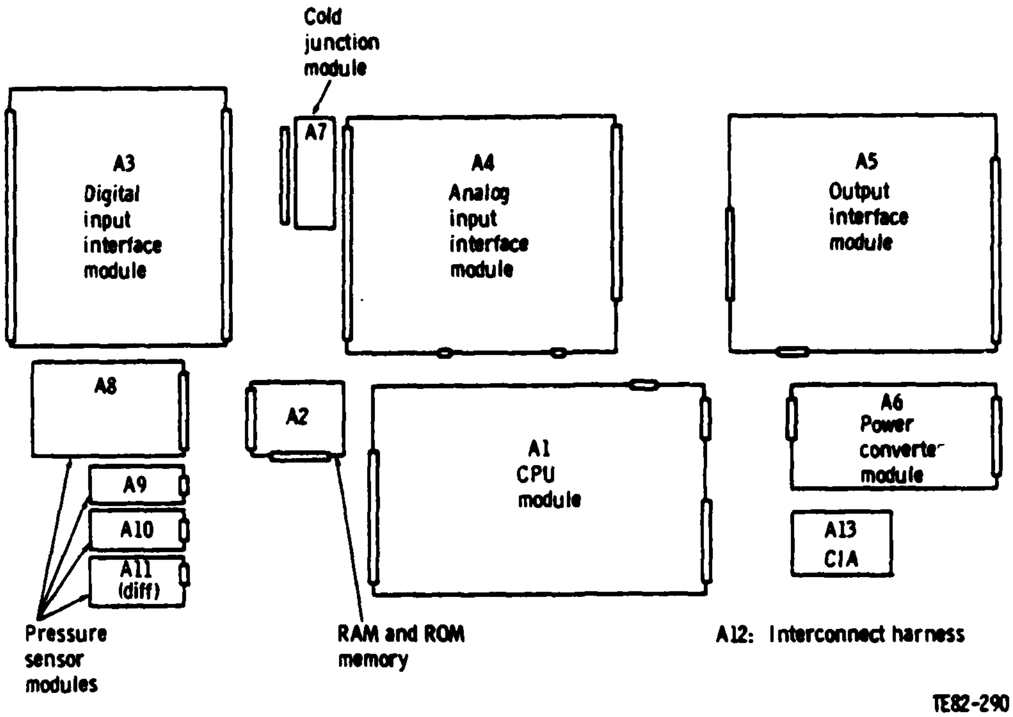

Figure 11. EH-K2 system partitioning--module level.

A1 Central Processor Module

The central processor module (Figure 12) is a completely self-contained microcomputer. Under program control the module checks and processes input data from sensors, performs the control calculations, and outputs data to operate effectors. In addition, the module provides memory-mapped I/O interface control and fault detection and restart control. The central processor module contains logic to implement the following functional areas:

- o microprocessor
- o microprocessor clock generator
- o interrupt priority encoder
- o control signal and processor flag logic
- o interval timer
- o watchdog timer
- o fault detection

A bit-slice based processor was selected as the computational element for the CPU module. This provides the following significant advantages:

- o compatibility with existing instruction set
- o high reliability bipolar technology
- o full temperature range of -55°C to +125°C
- o qualified to MIL-STD-883 Level B
- o 16 bit external data bus
- o 16 bit internal processing

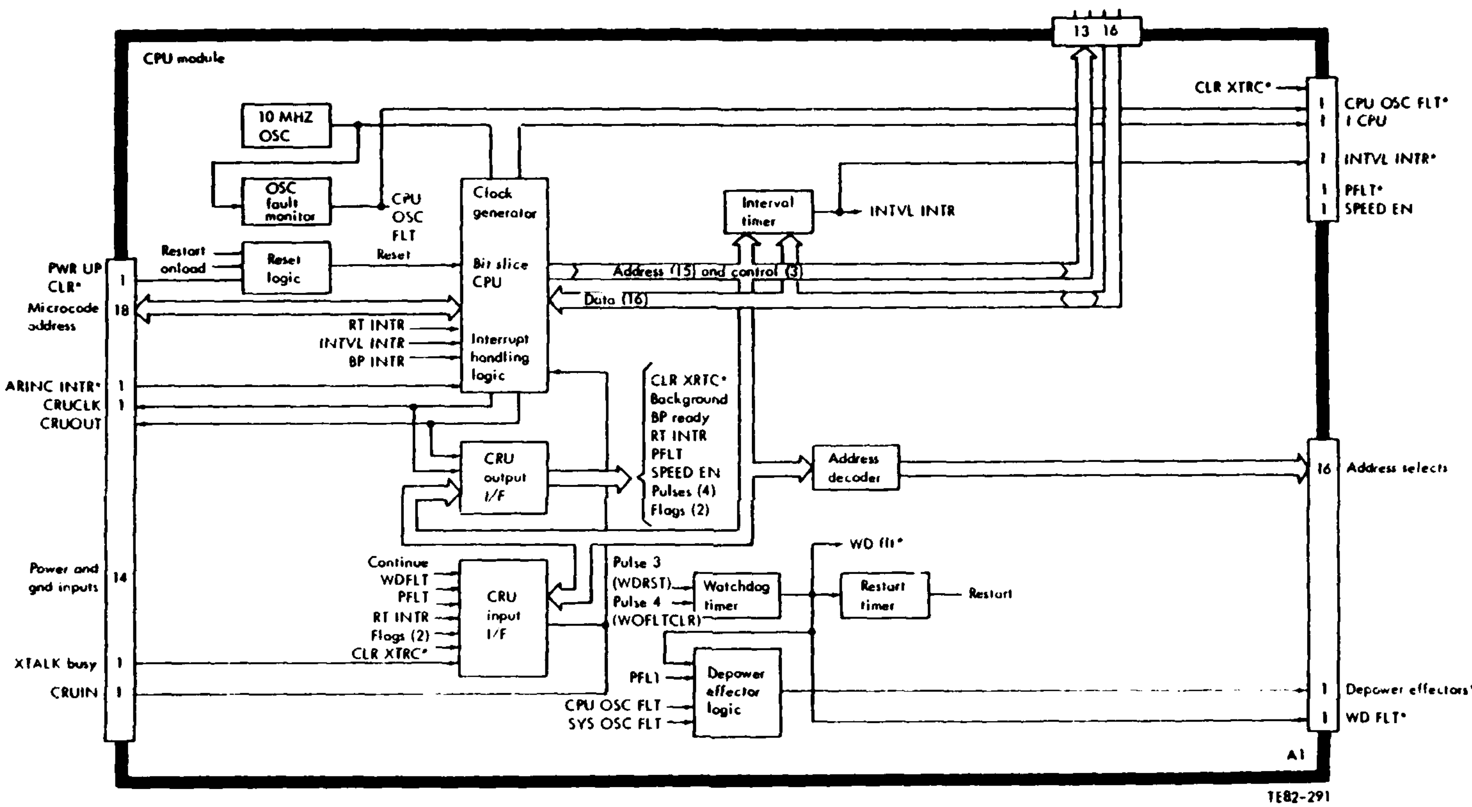

Figure 12. A1 CPU module.

- o extensive instruction set, including microcoded algorithm for table lookup and matrix operations
- o high throughput

The 16 bit internal processing capability of the processor is complemented by a complete word-length external data bus, providing increased throughput over other 16 bit microprocessors employing an 8 bit external bus. The 16 bit word length provides both the accuracy and throughput required by large scale turbine control applications.

The bit-slice CPU design was selected as the only feasible processor capable of executing the computational load required by the multivariable control mode in the required time.

A2 Memory Module

The memory module (see Figure 13) for the central processor consists of two sections: a read-only memory, which provides storage for the program, various constants, and tables, and a read-write random access memory, which provides working registers, I/O data storage, and a scratchpad for calculations. The dynamic RAM memory will be used for system development and engine bench tests. The dynamic RAM will be located on the A13, CIA module.

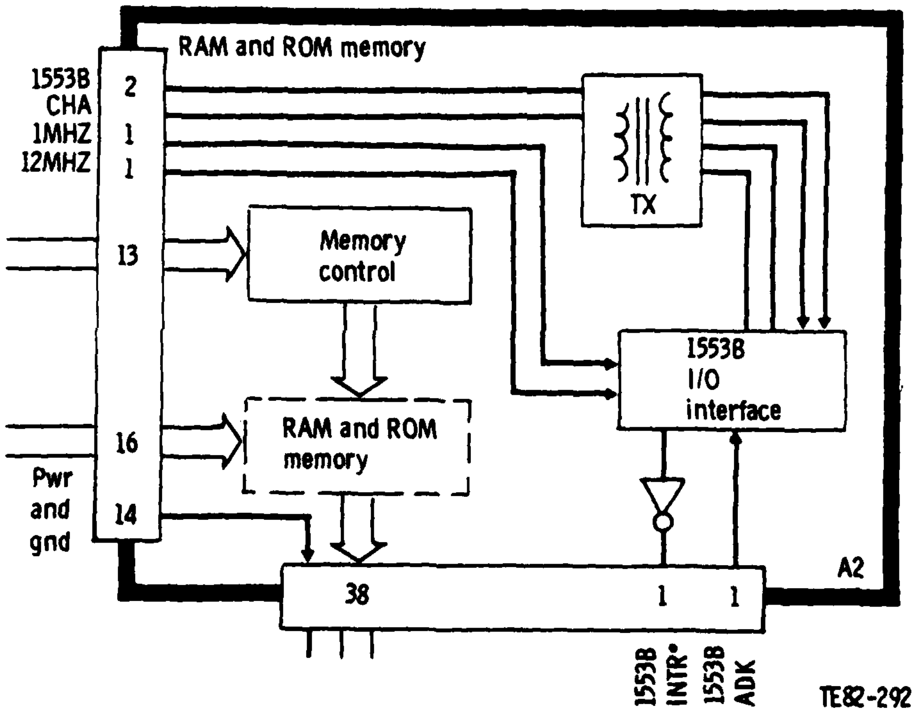

Figure 13. A2 RAM/ROM memory module.

In the flight version, bipolar fusible link Programmable Read-Only Memories (PROM) are utilized for program storage. Each PROM chip holds 8K eight bit words, and the program memory is organized to provide 24K 16 bit words of storage. Power switching circuitry is employed to remove power from the PROM when they are not being accessed, significantly reducing system power consumption.

The read-write RAM provides 4K words of temporary storage for use by the processor for workspace registers, memory-mapped I/O data storage, and calculation storage. The RAM is implemented with four large scale MOS memory chips, selected over other memory ICs for their high density, fast access, and internal power-down feature.

Associated logic on the central processor module is implemented to provide memory address decoding for memory chip selects and memory-mapped I/O block decoding. Memory-mapped I/O is a technique employed by the processor whereby I/O devices are assigned addresses in the normal memory address space; data are transferred to and from the devices by standard memory referencing instructions, eliminating the need for special I/O instructions and interface logic.

The 1553 Interface is based on MIL-STD-1553B defining a half duplex multiplexed transmission bus used for the exchange of information between the electronic control and the aircraft. The remote terminal will provide a communication link between the electronic control and other devices on the 1553 bus.

This interconnection provides the capability to share information without extra sensors and permits a greater effective redundancy level without additional hardware.

The remote terminal uses a high speed microcontroller operating independently of the electronic control CPU to control the various operations. The microcontroller checks all commands on the 1553 bus and determines the data exchange required if the command was for this terminal. All data exchanged are located in the engine electronic control (EEC) memory. The remote terminal accesses this information through direct memory access (DMA). This allows the most recent data to be available with the least interaction required between the control and interface. The interface performs the data format conversion between the serial Manchester encoded format used in transmission on the 1553 bus and the parallel form used in memory storage. The remote terminal uses parity, message length, and message gaps to ensure detection of any transmission errors.

<u>A3 Digital Input Interface Module</u>

The digital input interface module (Figure 14) contains the following:

- o optical crosstalk interface
- o speed signal conditioning and measurement
- o resolver demodulation
- o resolver excitation
- o system clocks

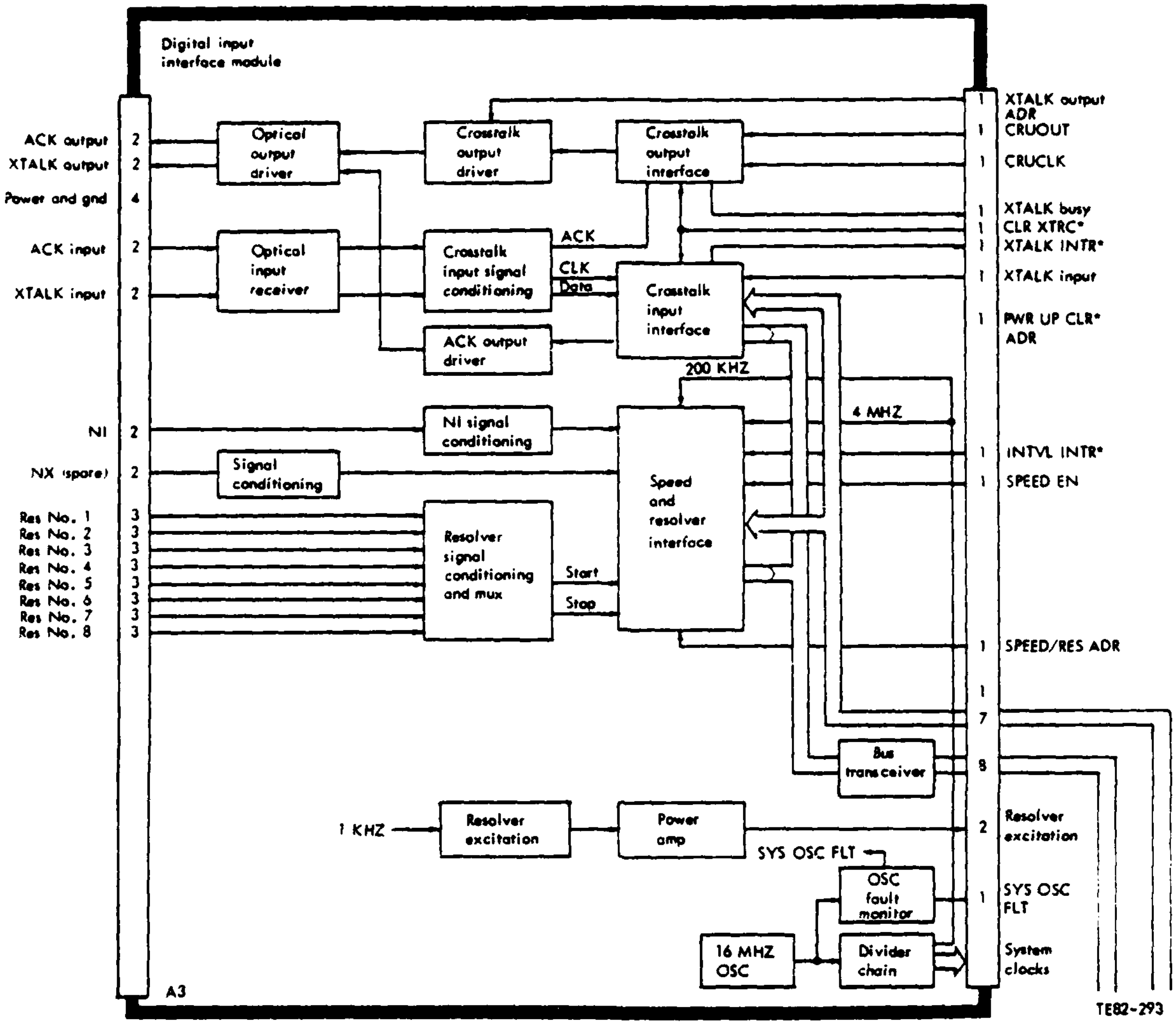

Figure 14. A3 digital input interface module.

Optical Crosstalk

A high speed 1M bit/sec data link will be incorporated in the module to allow serial crosstalk between the two EH-K2 controllers. The implementation will consist of high temperature optical fiber cable and a hybridized military transmitter and receiver capable of operating over a 37 meter range. The data will be formatted in Manchester coding. Presence or absence of crosstalk at the receiver will indicate the other controller's health to each CPU.

Speed Measurement

A frequency to digital speed measurement technique is used in the electronic control. The speed interface consists of analog to digital voltage level converters and a digital large-scale integration (LSI) speed microcircuit. The LSI speed microcircuit is capable of handling two independent speed channels

simultaneously. Each signal is first converted to logic levels and passed through a digital counter. By reading these two counters at 20 ms intervals, the microprocessor can compute speed with better than 0.015% of point accuracy over a greater than 10:1 speed range.

Resolver Demodulation

The resolver processing circuitry provides for multiplexing eight independent resolver feedback signals into the processing circuitry which converts the amplitude modulated resolver feedback signals into a 12 bit digital number proportional to the resolver feedback angle.

Essentially, a resolver gives two carrier signals that are amplitude modulated by the sine and the cosine of the mechanical rotation angle. The signal processing technique that is used to extract this mechanical rotation angle of the resolver is the zero crossing detection method. An R.C. bridge network is used to convert the amplitude modulated feedback signals into phase modulated signals. The "lead" and "lag" outputs of the phase shift networks are routed to zero crossing detectors that control the clock input to a set of binary counters. The clock is enabled (start) when the leading signal crosses zero and then disabled (stop) when the lagging signal crosses zero.

The EH-K2 will provide an accuracy of $\pm$15 minutes between 45 degrees and 225 degrees of resolver rotation.

Resolver Excitation

The resolver excitation is obtained by low pass filtering a 1kHz signal from the system clock. The low pass filter consists of three cascaded two pole Butterworth filters that generate a sine wave with less than 1% total harmonic distortion at 1kHz. This sine wave is then buffered and applied to the resolver power amplifier, capable of driving the inductive primaries of the eight resolvers.

System Clocks

All system clocks are derived from an accurate and stable crystal oscillator and appropriately divided down to supply various frequencies for the digital logic, resolver excitation, and other modules.

A4 Analog Interface Module (Figure 15)

Pyrometer Signal Conditioning

This module provides for pyrometer signal conditioning to be defined at a later date. Growth area on the module will allow for peak and average detectors, filtering, and fault tolerance. The buffered signals are supplied to the A/D converter for use in computational analysis.

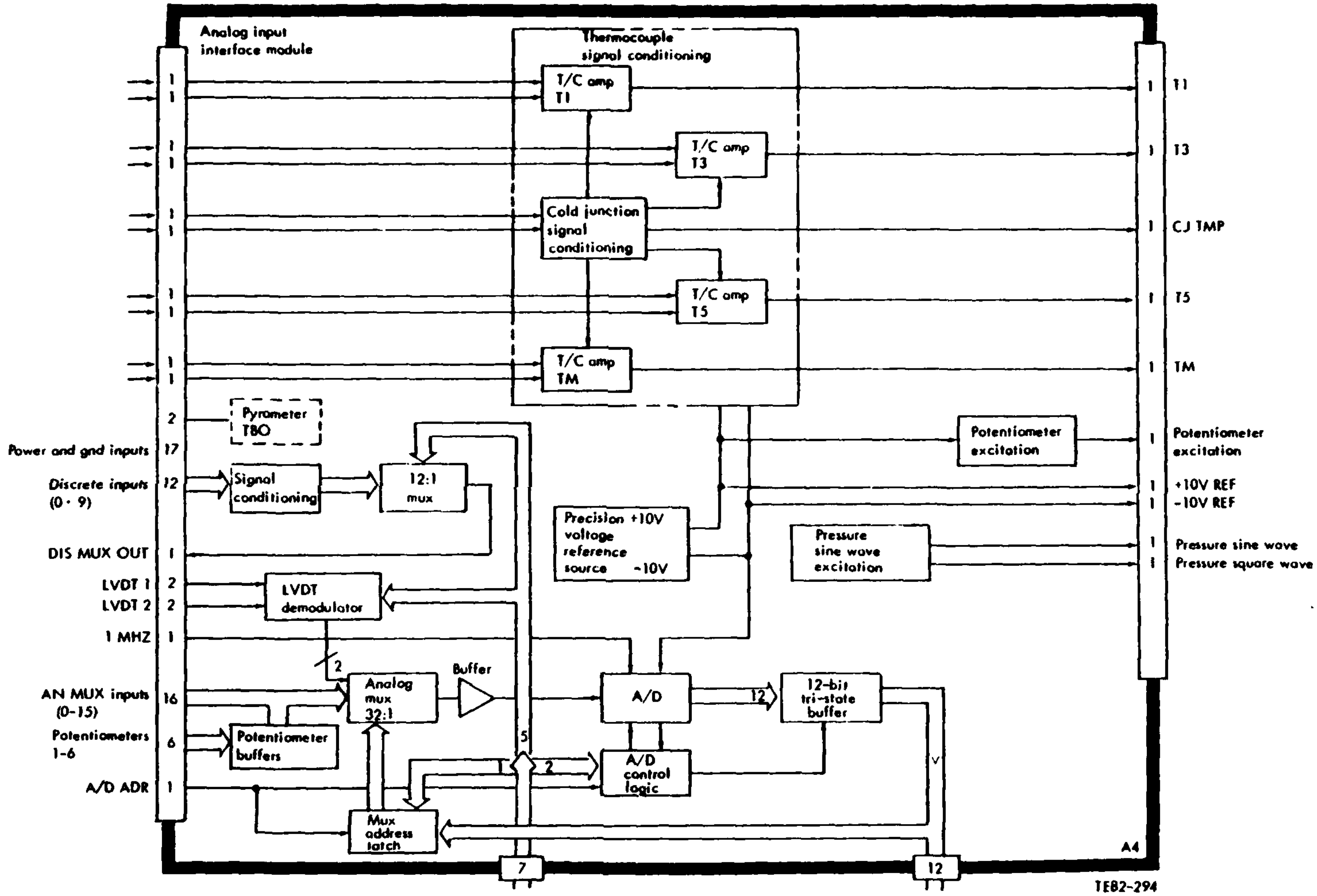

Figure 15. A4 analog input interface module.

LVDT Signal Conditioning

The secondary windings of the linear variable differential transformers (LVDTs) are demodulated here.

The secondary output of the LVDTs is supplied to a differential input buffer amplifier providing high input impedance, common mode signal rejection and input EMI filtering. The output of the buffer is capacitively coupled to an active half wave rectifier. The rectified signal is then smoothed with a two pole, low pass filter. The demodulator output is then fed to the A/D.

Precision Reference

The precision ± reference voltages used in input/output signal conditioning are developed from a precision +10 VDC reference integrated circuit whose output is inverted and buffered to provide adequate load capacity.

Cold Junction Compensation

Cold junction compensation is accomplished with a sensor generating current proportional to absolute temperature. It is a semiconductor device using transistor junction temperature sensitivity. The output is one microamp per degree Kelvin with an accuracy of 0.9°F over the temperature range of -55°C to +125°C.

The required circuit conditioning is a current to voltage conversion and an offset for zero centering at 32°F. The conversion to voltage (i.e., 0.04 volts/°C) is accomplished with current feedback applied to a precision operational amplifier. The cold junction voltage signal is then fed to the individual thermocouple temperature amplifiers to compensate for the effect of changes in cold junction temperature on the thermocouple output voltage.

Thermocouple Temperature Amplifier

The thermocouple signals are conditioned with an instrumentation type input amplifier followed by a mixer amp. The instrument type amplifier provides a floating input separated from ground enabling common mode rejection of extraneous signals and ground currents. The mixer stage provides for injection of cold junction compensation and zero offset reference signals isolated from the thermocouple input by the instrumentation input amplifier.

The first stage of the input amplifier is made up of two ultra low drift amplifiers. The second stage is a low drift amplifier while the mixer last stage is standard as permitted by higher signal levels. Critical gain resistors have close accuracy requirements.

Failure indication for open thermocouple is provided for by application of voltages to the input through large resistances. In normal operation, the drop at input is shorted out by the thermocouples, but when the thermocouple circuit is opened, this voltage is applied to input and gives full saturated amplifier output.

Analog Input Interface

Up to 32 analog inputs can be directly read by the processor by controlling an analog multiplexer and one analog to digital converter. Sub multiplexers, located on another module, provide for additional analog inputs. Approximately 25 microseconds are required to convert each selected analog input to a 12 bit digital word. Analog to digital conversion error for the proposed interface is no more than 30 mV over the analog input range of +10 to -10 volts.

A multichip analog to digital converter was chosen over monolithic types because the required conversion accuracy and speed could not be met with a monolithic converter. However, when monolithic converters that meet the performance requirements become available, their substitution for the multichip converter would improve the reliability of the analog input interface.

Pressure Module Excitation

The pressure module excitation circuitry produces two signals, the sine wave excitation and the reference signal. Two operational amplifiers are configured as a quadrature oscillator to generate a sine wave output. The oscillator is capacitively coupled to a buffer amplifier to remove any d.c. component in the signal. A series resistor at the buffer output provides phase stability for capacitive loading of the sine wave excitation. A phase-shifted square wave is provided as a demodulation reference for the pressure module. This reference is generated by phase shifting the oscillator output and converting it to a square wave with a zerocrossing detector.

Potentiometer Interface

Potentiometer reference is supplied by buffering the precision +10.00 volt reference. This buffered signal is then applied across the potentiometers with respect to analog ground. The potentiometer wiper outputs are supplied to the potentiometer buffers.

Two quad operational amplifiers allow for the buffering of six d.c. potentiometer inputs. The buffered signal is then applied to the analog multiplexer input.

A5 Output Interface Module (Figure 16)

Torquemotor Drivers

The torquemotor driver is a closed loop current driver sensing torquemotor currrent.

As the command request is increased, the torquemotor current increases proportionally, causing the actuator to change position. An indication of current through the torquemotor is provided to the multiplexer by a current sense feedback circuit. The current feedback signal also provides fault status of the torquemotor driver to the microcomputer. The use of a current driver minimizes the effect of coil resistance change with temperature. Each torquemotor driver utilizes its own digital to analog converter, eliminating the problems associated with capacitor hold times of sample and hold circuitry.

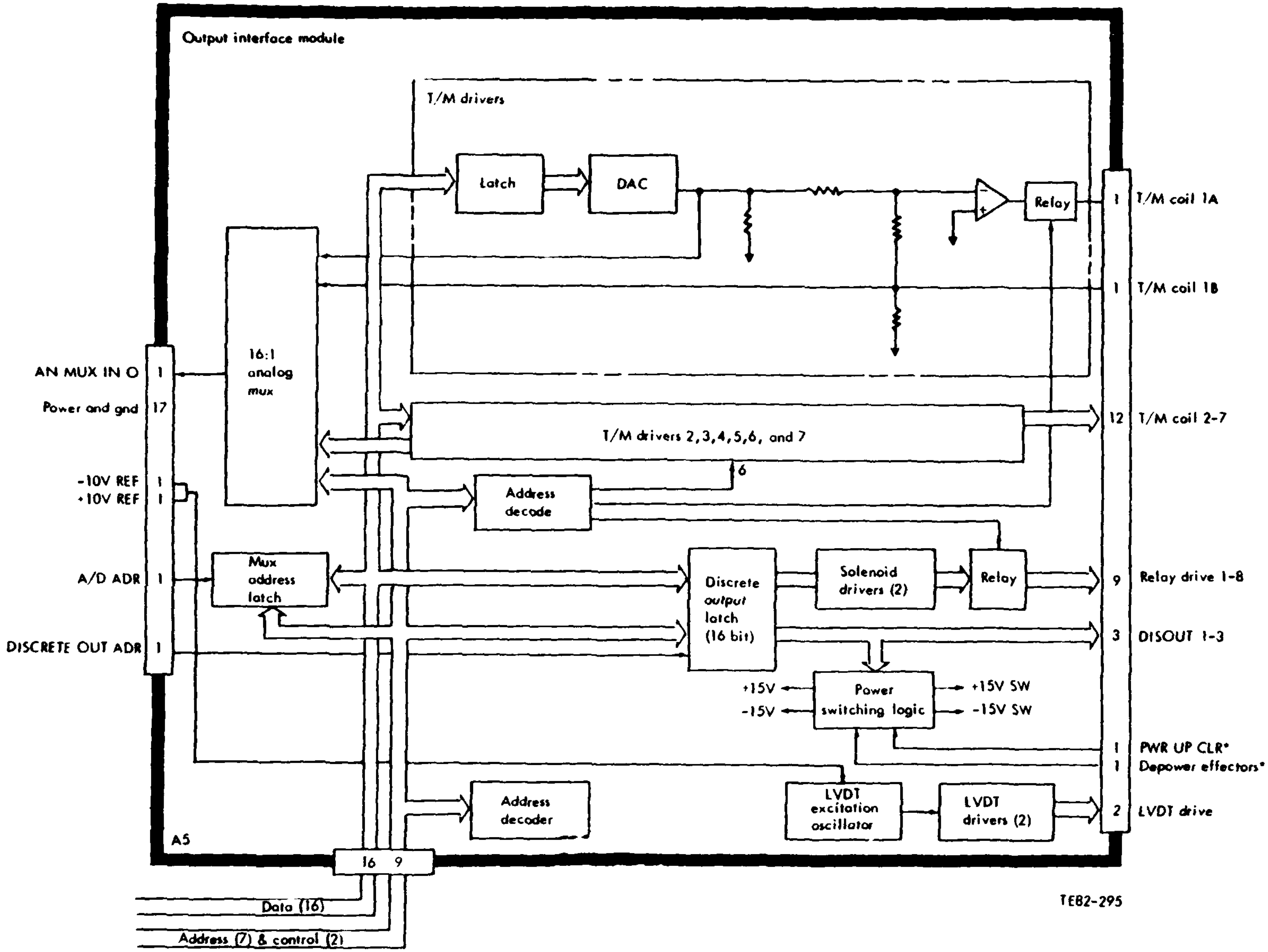

Figure 16. A5 output interface module.

LVDT Excitation

The excitation for the LVDTs consists of a precision triangle wave generator, whose amplitude is accurately controlled by comparing the integrator output with the precision reference voltages. The output then commands the integrator to alternately generate the positive and negative slopes of the triangle wave output. A power buffer stage is used to drive the primary winding of the LVDTs. The excitation determined by the characteristics of the LVDTs will be 20 volts peak to peak at 3000 Hz.

Solenoid Drivers

The solenoid drivers provide power for the control of external solenoids. The driver circuitry consists of a high gain transistor stage that provides for short circuit protection and is transient suppressed to reduce radiated emissions. The driver circuit provides for current monitoring, which is submultiplexed and fed back to the CPU for fault monitoring.

A6 Power Converter Module (Figure 17)

Power Conditioning

As shown in the system block diagram, either a permanent magnet alternator (PMA) or aircraft 28 volts can be used to power the electronic control.

PMA Source

To reduce the number of components used, the alternator is operated in a current mode. This mode of operation produces a PMA output that remains somewhat constant for a wide range of load currents. The output voltage however varies proportional to PMA speed. For this application the rectified PMA output voltage will be designed to remain within a voltage range of 18 to 36 VDC over an engine speed range of 10% to 110%. This approach will allow the aircraft 28 volts to be used for ground check and as emergency backup. A separate set of windings provide power for the solenoids.

Power Converter

The power converter is a push pull switching converter designed to provide 5.0 $\pm$ 0.25 VDC at 8A and $\pm$ 15.0 $\pm$ 0.75 VDC at 1 amp at an input voltage range of 18 to 36 VDC, making it compatible with the two power sources. Provisions are also made for +28 VDC to power solenoids and a -30.0 VDC for use with electrically alterable ROMs.

Input power is fed through the input filter to the logic and to the primary of a transformer. The control circuit provides a pulse train whose duty cycle is controlled by the feedback output sense voltage. This pulse train is fed to a transistor that switches the primary current of the transformer, ensuring a regulated supply voltage.

In addition to the power switching circuits, a circuit that monitors the output voltage is used. The circuit supplies a TTL compatible logic output whenever the output voltages are within their specified levels. This signal is used to

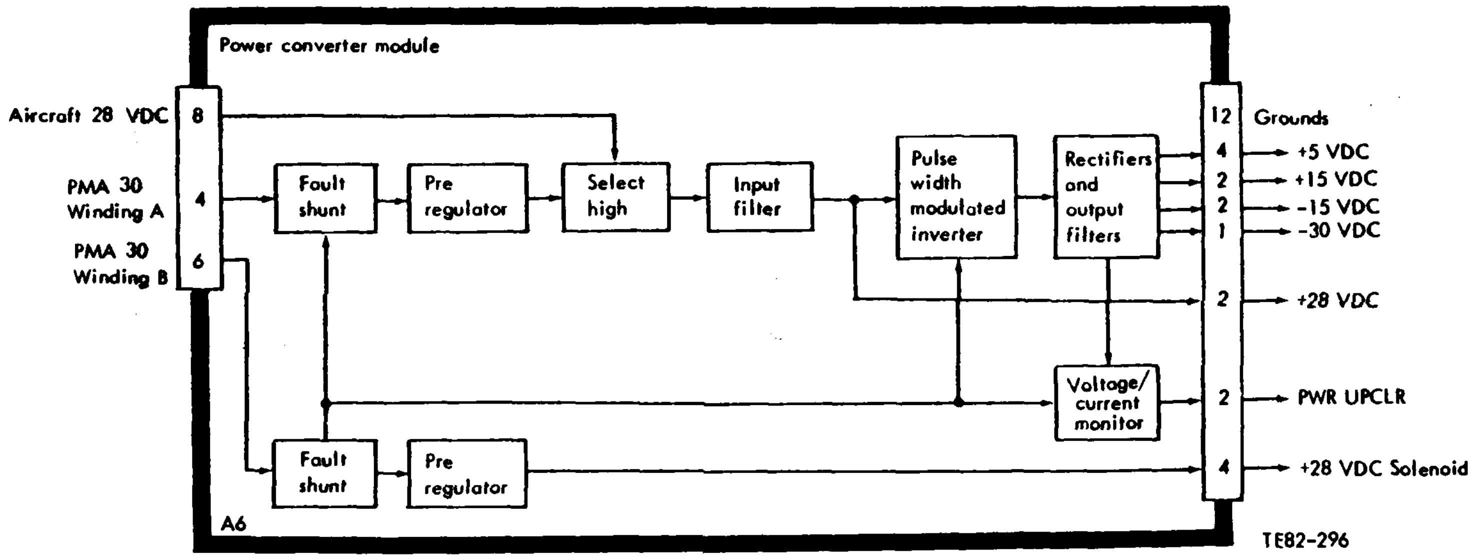

Figure 17. A6 power converter module.

both initialize the processor and enable power to the torquemotors. This logic is active, down to an input level of 5 volts, preventing any spurious torquemotor outputs.

The converter is fully protected against conducted interference and transients as defined in MIL-STD-461B, and the input is protected against 600 volt spikes. The input transistors have collector to emitter breakdown voltages in excess of the 80 volt surges.

The converter is designed to meet the conducted emission requirements on its A/C 28 VDC power leads per MIL-STD-461B. Inductors, ferrite bead assemblies, and capacitors are used to prevent both high frequency and low frequency internally generated interference from being conducted to the aircraft power source and generator.

A7 Cold Junction Module

The cold junction module (Figure 18) contains four thermocouple junction transitions from thermocouple wire to copper wire. The thermocouple temperature sensing device is positioned in this module to obtain an accurate cold junction temperature. The entire assembly is potted in an epoxy plastic to maximize thermal inertia for accurate temperature measurement and mounted in the EH-K2 housing/connector area near the I/O connectors.

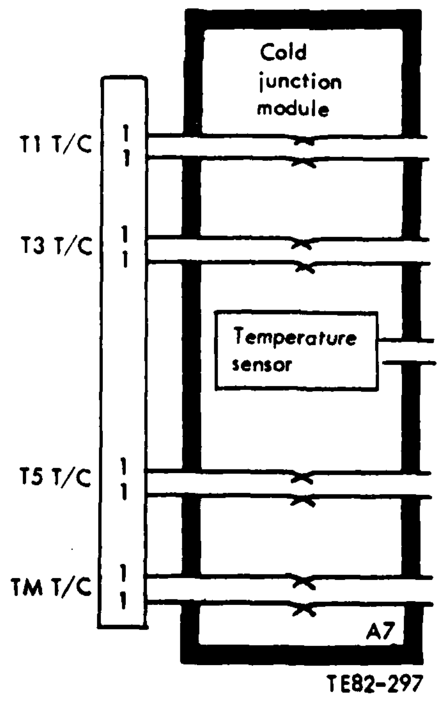

Figure 18. A7 cold junction module.

A8 All Pressure Modules

The pressure subsystem (Figure 19) uses a Bendix quartz capacitive pressure sensor in a closed loop capacitance bridge. This capacitance bridge is balanced digitally through the microcomputer to minimize parts count and provide constant loop response characteristics over the pressure range. A temperature sensor is located close to the sense element to provide accurate temperature compensation. The pressure subsystem also includes a calibration PROM located on the pressure module which provides linearization and temperature compensation data to the microcomputer.

Key features of the pressure subsystem are as follows:

- Accuracy: Bendix Energy Controls Division has conducted an extensive survey of available pressure sensing devices. No other device has yet to be found that can survive the temperature and vibration environment while maintaining excellent accuracy. Absolute pressure transducer accuracy requirements for the GMA200/1 have been specified at 0.5% of point over pressure turndown ranges of 37:1 for inlet total pressure, 38.5:1 for compressor discharge pressure and 15:1 for exhaust nozzle pressure. However, the compressor discharge pressure sensor is required to transduce pressure over a 96.25:1 turndown range at a reduced accuracy. Test results on the compressor discharge pressure transducers show that the transducers are achieving 0.5% of point accuracy over the entire 96.25:1 turndown range with the ambient temperature varied over the full unit environmental temperature range. Typical worst case accuracy of the transducers over the normal working range is 0.2% of point.

- Ruggedness: This sensor does not have any type of inherently delicate bellows or beam structure internal to it; i.e., it has no moving parts. It requires no special shock mounting other than that required for printed wiring boards. This sensor was used in a 747 test program, mounted on engine, with no sensor failures in over 2400 hr of operation. Also, one of the devices was accidentally exposed to a greater than 10X overpressure without a shift in reading. There have been <u>no</u> vibration or overpressure related failures of the sense element.

- Module interchangeability: Since all linearization and temperature compensation information is stored in a PROM located on the pressure sensor module, the pressure sensors are completely interchangeable from EH-K2 to EH-K2 without controller recalibration.

A12 Interconnect Harness

The EH-K2 interconnect harness provides for a means of routing signals between modules in a structured manner which reduces crosstalk and noise. The test stand EH-K2 will utilize wirewrap zero insertion force module edge connectors routed to the external I/O connectors, which are wirewrapped to facilitate customer/vendor changes.

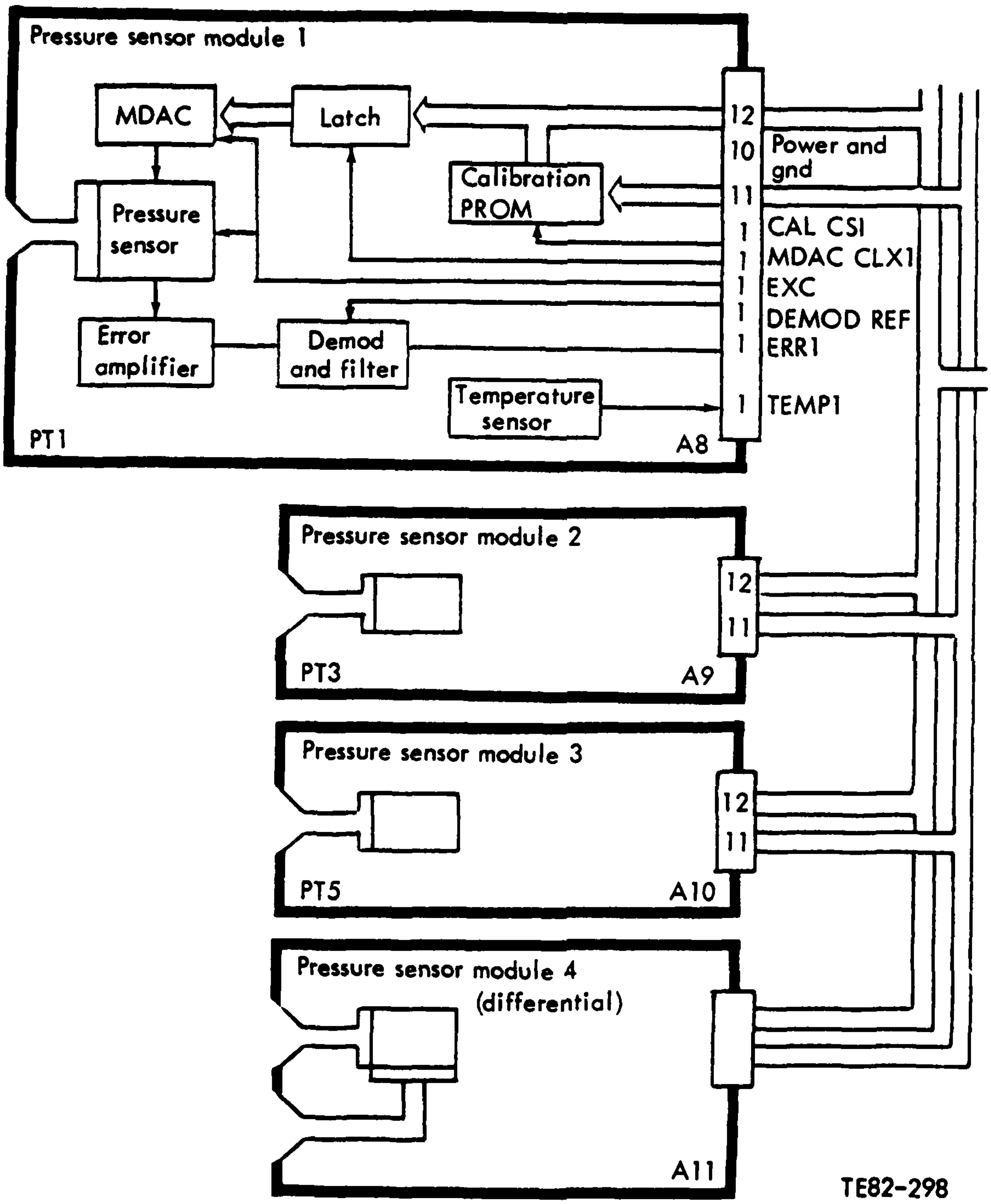

Figure 19. Pressure sensor modules.

A13 CIA

The communications interface adapter (CIA) consists of a module capable of communicating with the EH-K2 CPU via a board connector. The CIA module will house the system's development RAM memory and will be part of the controller package during engine control development. This Dynamic Random Access Memory can be downloaded via the CIA's external connector that allows data exchange with a EK-39 test console which contains a Texas Instruments DS990/4 Floppy System. The CIA will receive an uninterruptable power source form the EK-39 to ensure that the CIA's RAM never loses power when the controller is powered down. With the CIA, an operator is capable of interactive monitoring of the CPU during normal operation by means of the EK-39's CRT or stored data on floppy disk. The operator is capable of setting breakpoints for monitoring calculations, modifying parameters in the controller, generating test signals, and manually commanding inputs.

V. GMA200 CONTROL SYSTEM DESCRIPTION

The GMA200 control system is configured as shown in Figure 20. There are seven electromechanical outputs, including fuel flow metering, a fuel flow divider, variable geometry in the turbine and compressor, exhaust nozzle area, and two cooling bleed flows. Also shown are sensor inputs (four pressure, four temperature, and two speed), an optical data link (for communication with an optional redundant controller), and an optical pyrometer TBT sensor.

FUEL SYSTEM

The GMA200 will employ a fuel system (see Figure 21) similar to the TRW pump and Woodward metering system designed for the GMA200 JTDE. The fuel pump/control assembly consists of (1) an inducer element that keeps the main centrifugal element filled with fuel at all inlet pressure conditions, (2) a retracting vane starting pump, (3) a high pressure centrifugal impeller surrounded by a free wheeling rotating diffuser to reduce drag friction, and (4) a pressure drop type metering control that consists of a metering valve, torquemotor operated fuel servo, throttling valve, and pressurizing valve.

The metering valve control assembly will be built by Woodward Governor, Rockford, Illinois, and supplied to TRW, where the combined fuel pump/control assembly will be assembled and tested prior to being shipped to DDA. The metering control contains a torquemotor that uses a signal from the engine electronic control to operate a fuel servo valve that controls the amount of fuel going to the engine. Downstream of the metering valve is a throttling valve whose function is to control the pressure drop across the metering valve to a fixed value. Since fuel flow is a function of metering valve area and its pressure drop, fuel flow to the engine is controlled directly by the electrical signal to the torquemotor servo. Throttle valve position is determined by a spring and a regulated fuel pressure, which is generated by a differential pressure sensor that measures pressure drop across the metering valve. A pressurizing valve is located downstream of the throttle at the control exit. Its function is to maintain a more nearly uniform gain over the flow range.

The GMA200 will have an integral flow divider. The present conceptual design requires the digital controller to calculate fuel/air ratio and to generate an electrical signal that is used in the flow divider to operate a fuel servo valve. The servo valve meters fuel to the main fuel nozzle system to maintain, after transition, equal fuel flow in the primary and main fuel nozzles over the flow range. A shutoff valve may also be incorporated into the flow divider.

ACTUATORS

Compressor Geometry Actuation System

The compressor vane actuation system will probably be a fuel powered hydraulic actuation system controlled on corrected speed by the digital controller through an electro-hydraulic servo valve (EHSV) and a position transducer. A pair of hydraulic cylinders will actuate a bell crank system to each vane actuation ring, one per stage of variable vanes. LVTDs sense actuator travel and provide position feedback to the controller.

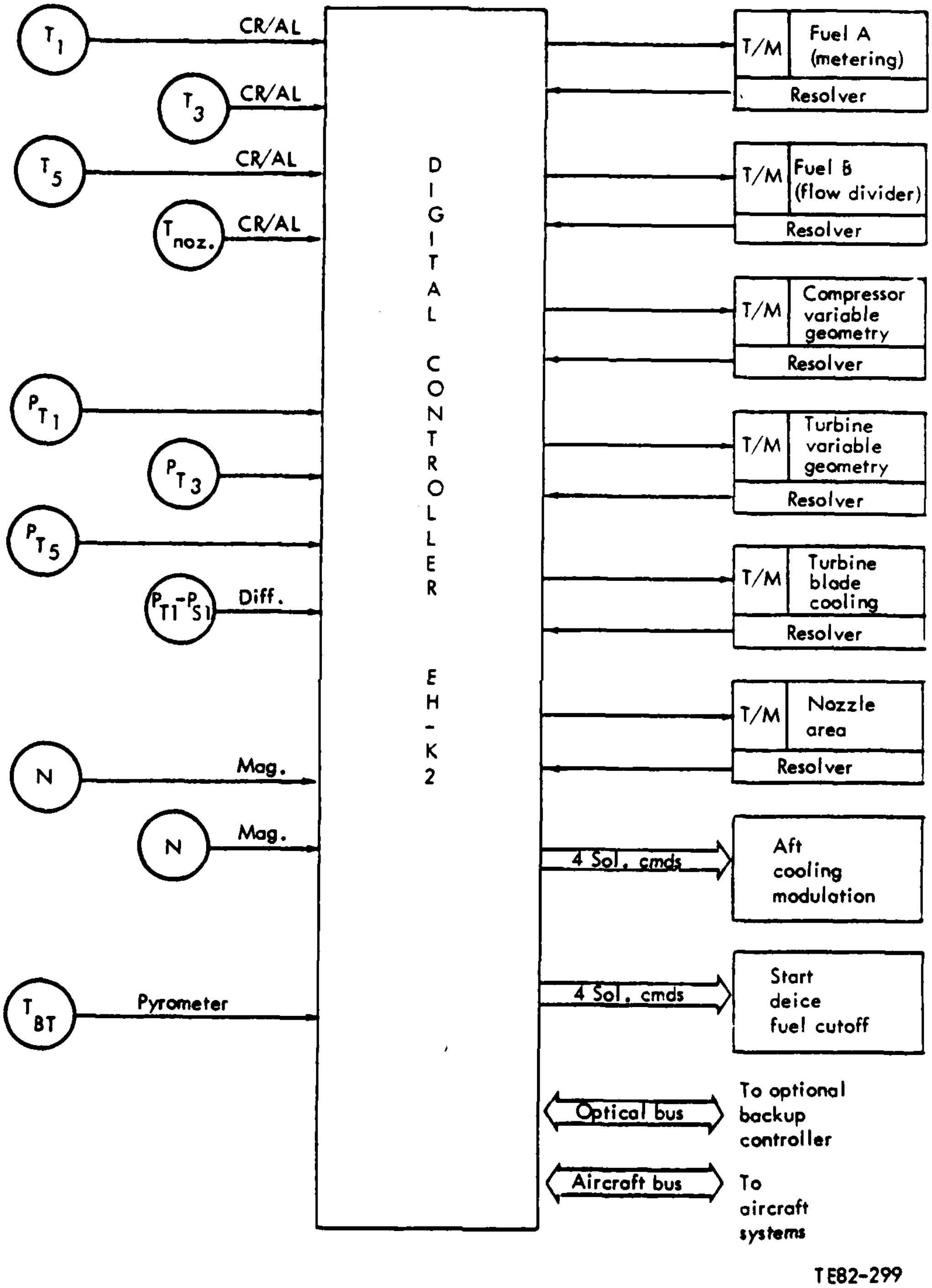

Figure 20. GMA200 control system.

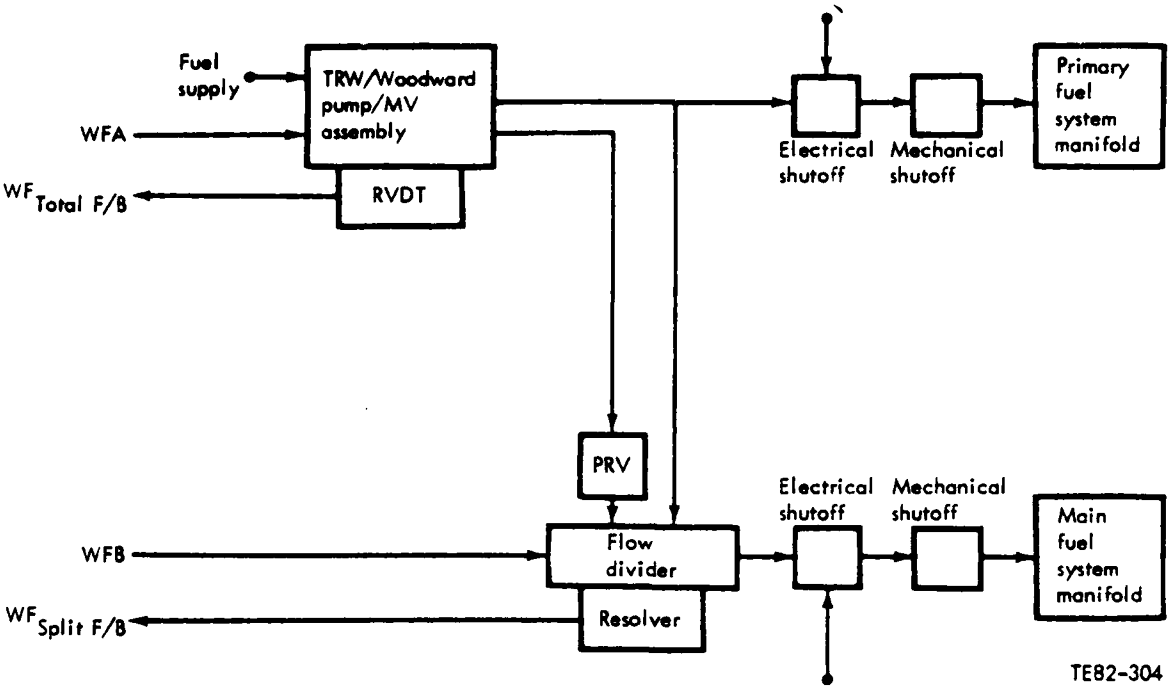

Figure 21. GMA200 fuel system schematic.

Turbine Geometry Actuation System

The turbine actuation system was developed on a Navy contract to survive the high temperature environment of the GMA200 JTDE. The turbine actuation system, shown in Figure 22, has a pneumatic motor that drives multiple planocentric actuators located around the periphery of the engine by means of a high speed flexible drive cable system. The actuators in turn position a sync ring. An electrical signal from the digital controller modulates the air supply to the motor to control the sync ring rotational rate and direction. Resolvers provide position feedback to the controller.

Turbine Blade Cooling Actuation System

The GMA200 design incorporates turbine blade cooling to limit turbine blade metal temperature. Compressor discharge air is directed onto the turbine blades by 30 individual poppet valves. These valves are activated by venting the control port to atmosphere. These control ports may be individually controlled or manifolded together.

A turbine blade cooling scheme using four on/off solenoid valves is shown in Figure 23. Four discrete signals are provided from the digital controller to operate the four solenoid valves. The solenoid valves are connected to manifolds W, X, Y, and Z, which control 16, 8, 4, and 2 poppet valves respectively. The computer selects the number of valves with a binary logic, as shown in Table 5. Note that this allows selection of cooling airflow in 16 discrete (and equal) steps from 0 to 100% flow.

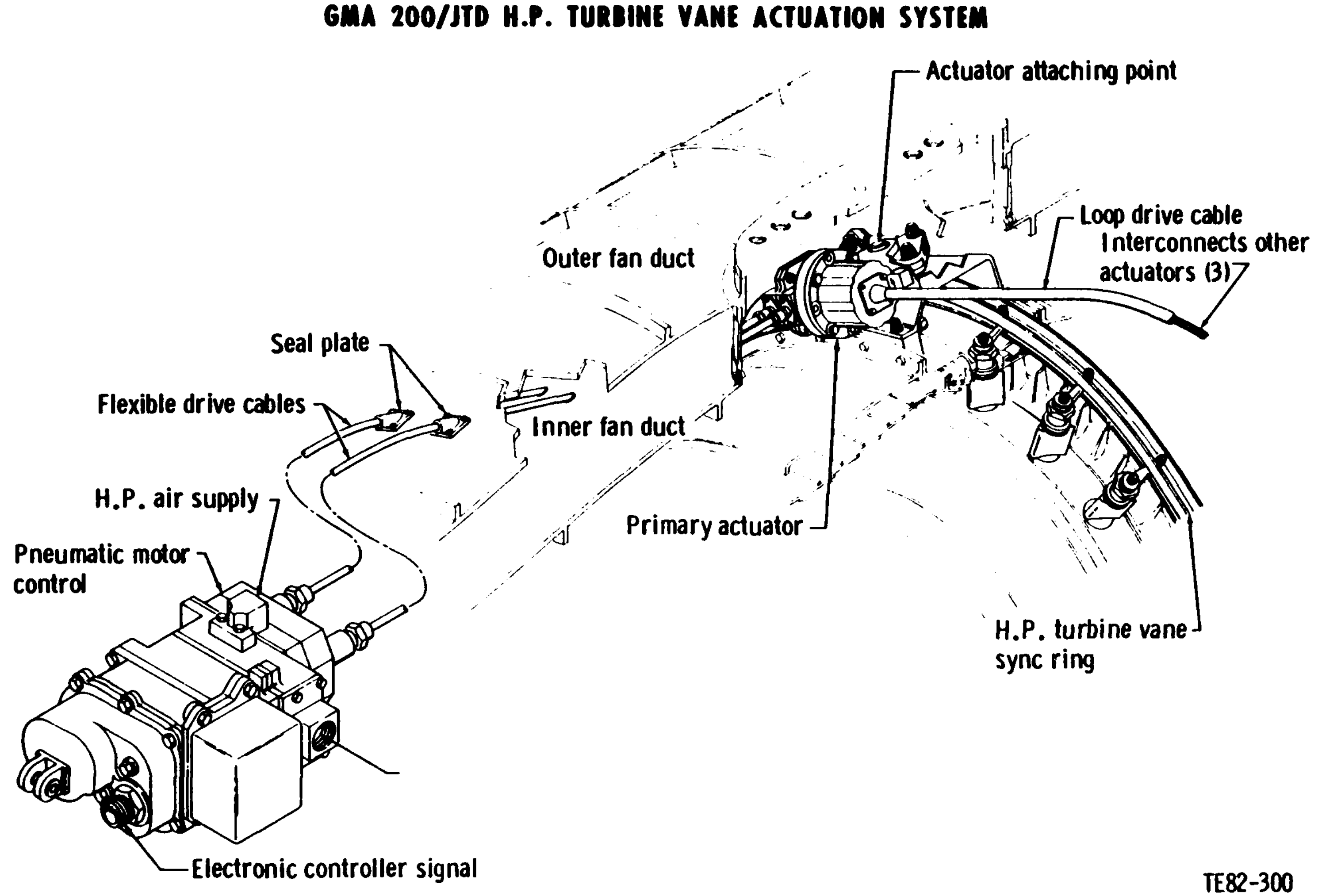

Figure 22. HPT vane actuation system.

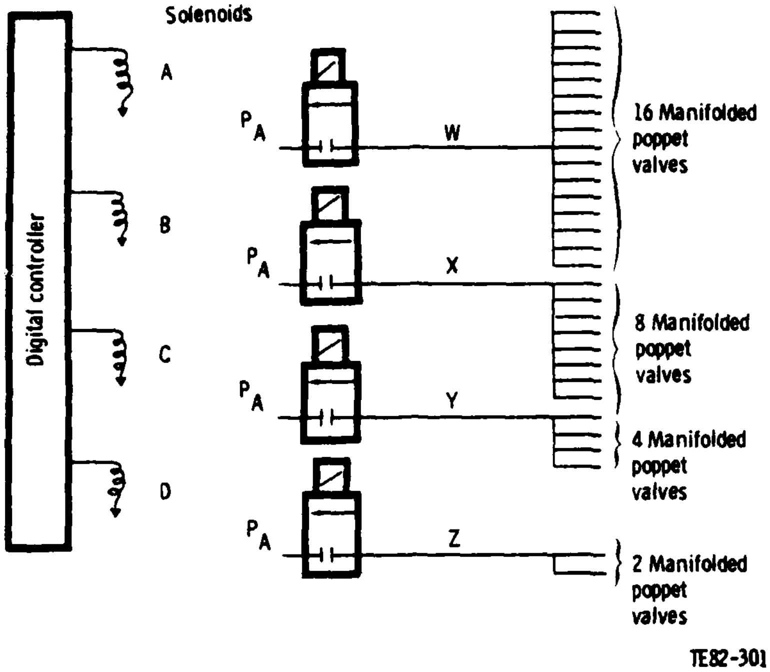

Figure 23. HPT cooling system.

Aft Section Cooling Modulation

This system will probably consist of a ring-valve similar to the LPT turbine "jet flap" control on the GMA200 JTDE (see Figure 24). An air motor and planocentric could be used here because the ring valve and planocentric drives would be in the rear support area (hot section) and the air motor in the compressor section similar to the HPT arrangement.

Nozzle Area Actuation System

The nozzle actuation system may be an airmotor drive through ball screw jacks to move the mechanically linked convergent and divergent sections of the nozzle. This arrangement is similar to the current F100 system in which the ball screw jacks survive well in the hot section while the airmotor is located in the cooler compressor section.

ENGINE SENSORS

Engine sensors that interface with the digital controller include the following:

- o temperatures (4)
- o pressures (3 absolute, 1 differential)
- o speeds (2)

The GMA200 sensed variables and proposed instrumentation are included in Table 6.

Table 5.
Control logic truth table.

Solenoid state				Number of poppets					%
A	B	C	D	W	X	Y	Z	Total	Flow
0	0	0	0	0	0	0	0	0	0.0
0	0	0	1	0	0	0	2	2	6.7
0	0	1	0	0	0	4	0	4	13.3
0	0	1	1	0	0	4	2	6	20.0
0	1	0	0	0	8	0	0	8	26.7
0	1	0	1	0	8	0	2	10	33.3
0	1	1	0	0	8	4	0	12	40.0
0	1	1	1	0	8	4	2	14	46.7
1	0	0	0	16	0	0	0	16	53.3
1	0	0	1	16	0	0	2	18	60.0
1	0	1	0	16	0	4	0	20	66.7
1	0	1	1	16	0	4	2	22	73.3
1	1	0	0	16	8	0	0	24	80.0
1	1	0	1	16	8	0	2	26	86.7
1	1	1	0	16	8	4	0	28	93.3
1	1	1	1	16	8	4	2	30	100.0

SYSTEM FUNCTIONAL REQUIREMENTS

System Redundancy

The GMA200 digital controller will have the capability to operate as a dual redundant system. That is, provision will be made for two digital controllers to communicate through an optical data link.

Each digital controller will then operate on shared information from the pilot, airframe (flight controller and inlet), engine sensors, and control sensors to develop the required control commands to the fuel system and geometry actuation systems. One digital controller shall be designated as the primary controller and will issue all commands until it has determined that it has failed. Then the control task shall be delegated to the second digital controller. The primary digital controller issues commands to auxiliary systems for start-up, shutdown, ignition, de-icing, and failure accommodation. The primary digital controller will also furnish engine operating condition data to other aircraft systems (i.e., inlet control, pilot display, diagnostics, etc.).

External Inputs and Outputs

All external inputs to the control system will be via a MIL-STD-1553 data bus. These inputs include the following:

- o pilot command (PLA)
- o mode selection
- o ambient conditions
- o aircraft angle of attack
- o altitude and Mach number
- o inlet information

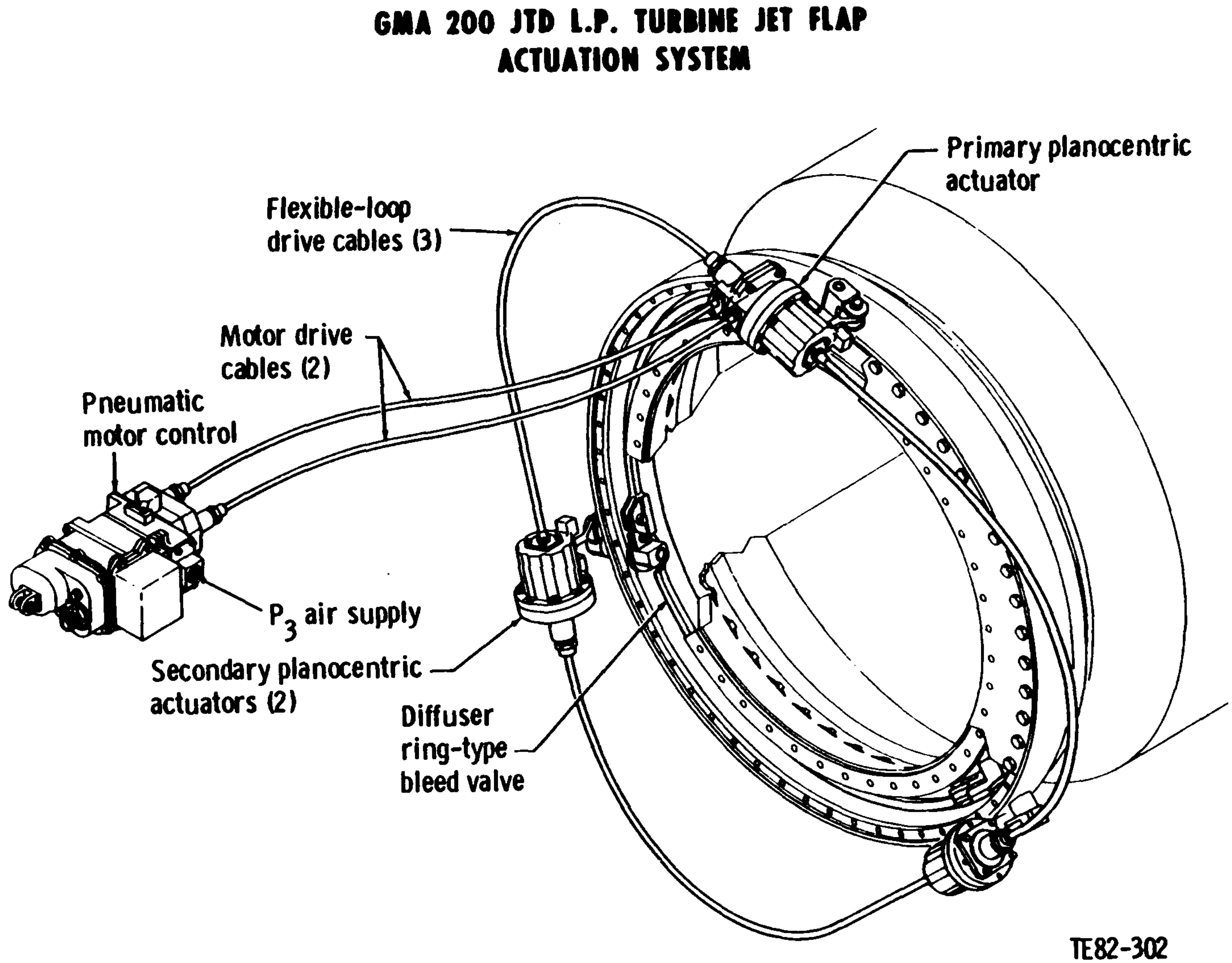

Figure 24. GMA200 JTDE LP turbine "jet flap" actuation system.

Table 6.
GMA200 sensor requirements.

Variable	Type of Probe	Range
Compressor inlet total pressure	Multiple rakes--manifolded	1 to 35 psia
Compressor inlet static pressure	Multiple rakes--manifolded	1 to 35 psia
Compressor discharge total pressure	Multiple rakes--manifolded	5 to 375 psia
Compressor discharge static pressure	Multiple rakes--manifolded	5 to 375 psia
Nozzle total pressure	Multiple rakes--manifolded	10 to 150 psia
Rotor speed No. 1	Magnetic	
Rotor speed No. 2	Magnetic	
Compressor inlet temperature	Chromel/alumel T/C--multiple parallel elements	350 to 800°R
Compressor discharge temperature	Chromel/Alumel T/C--multiple parallel elements	300 to 1650°R
Exhaust nozzle gas temperature	Thoriated platinum/platinum--40% rhodium--single element	400 to 3250°R
Turbine blade metal temperature	Optical pyrometer	1700 to 2200°R
Exhaust duct metal temperature	TBD	TBD

The control system will also supply information to other aircraft systems via the same data bus. This information shall include the following:

- o airflow demand to inlet control
- o engine diagnostic information
- o pilot displays

Sensing of Engine Operating Conditions

The operating condition of the engine will be determined through sensed temperatures, pressures, speeds, and geometry positions in the engine with dedicated control sensors.

Thermocouples and an optical pyrometer will sense the gas temperatures and metal temperatures necessary to properly control the engine behavior. Thermocouples will be used at the compressor inlet, the compressor discharge, and the exhaust nozzle inlet to sense gas temperatures at these locations. An optical pyrometer that measures the metal temperature of the turbine blades and

thermocouples will determine the average metal temperature of selected sections in the aft section.

Rakes and separate dedicated control sensors will be used to detect engine operating pressures in the form of pneumatic signals. Compressor inlet pressure and turbine outlet pressure will be sensed by multidepth rakes built into the struts and manifolded to provide an average total pressure at each of these locations. Six fuel nozzles are instrumented and manifolded to sense the pressure of the secondary air around the combustor and corrected in the software to yield compressor discharge total pressure.

A magnetic pickup located in the gearbox will provide the input signal to the engine speed counting circuit in the controller.

<u>Sensing of Control System Conditions</u>

Control actuator position feedback will be provided to ensure that the fuel loop and the actuator loops are properly closed. Feedback of the fuel metering valve position permits the fuel loop to be properly closed with respect to absolute fuel flow request. Similarly, effector positions are fed back from the compressor variable vane, the turbine variable vane, modulated cooling, and the variable area exhaust nozzle actuation systems.

Additional electrical cabling is required for electrical power and a digital data bus.

<u>Transmission of Sensed Signals</u>

Electrical harnesses will be provided to transmit the sensed temperatures, speeds, and positions to the controller. Lines will be provided to transmit pneumatic engine pressure signals back to pressure transducers that reside in the engine-mounted controller. Optical transmission capability will also exist for the optical pryometer. An optical digital communications linkage will exist between the two digital controllers.

<u>Fuel Pumping and Metering</u>

The fuel system will provide pressurized metered fuel to the main and primary fuel nozzles in the staged combustion burner. A pump will pressurize fuel from the aircraft using mechanical power from the engine gearbox. A zero leakage fuel shutoff and manifold drainage capability will be provided to shut the engine off. The metering valves, fuel flow measurements, and flow splitter valve must interface electrically with each digital controller.

<u>Geometry Actuation Systems</u>

All actuation systems must provide an electrical command and feedback interface with each digital controller.

The compressor surge margin is increased by scheduling compressor variable vane position versus corrected speed. Dual linear actuators will impart linear motion to a bell crank mechanism connected to the vane actuation rings. The motion of the actuators must be synchronized to prevent binding of the bell crank mechanism.

The flow capacity of the turbine is varied by mechanically varying the angle of the turbine inlet guide vanes. The vanes are positioned by imparting rotary motion to a circular sync ring located outside the turbine case.

The requirements for the compressor discharge nozzle actuation system are undefined. The nozzle may require one or two independent actuation systems.

Compressor discharge air is directed into the turbine blades by 15 pairs of poppet valves. Each pair of valves is held closed with compressor discharge air at a control port and activated by venting the control port to atmosphere. These control ports may be individually controlled or manifolded together.

Aft section cooling consists of modulated fourth-stage bleed air directed to the nozzle, rear support area, and tailpipe. The fourth-stage bleed air will be supplied to the aft section through eight external ducts with either individual on-off control of the air flow in each duct (controlled in opposing pairs) or continuous modulation at a common manifold for all eight ducts.

Starter and Ignition System

The starter system will consist of a starter motor and starting solenoid. The ignition system will consist of exciters, igniters, and auto-reignition provisions.

Power System

The control system will operate off of a permanent magnet alternator during normal operating conditions and aircraft 28 VDC power in the event of a primary power failure.

De-icing System

Provisions will be made for controlling flow of compressor discharge air back to the engine inlet for the purpose of de-icing.

Pilots Controls

The pilot will be supplied with a power lever to select engine operating point and the necessary switches or buttons to initiate starting, ignition, de-icing, and mode selection. Engine temperature, speed, fuel flow, and nozzle pressure will be displayed to the pilot.

Airframe Interface

Signals representing ambient conditions, Mach number, and angle of attack will be provided to the control from the flight control system. The control will supply airflow demand to the inlet.

Monitoring of Engine and Control Conditions

The control system will be responsible for monitoring engine conditions and control system conditions critical to proper controlled engine behavior. The control system will also provide communication capabilities such that the engine/control state can be monitored and/or recorded.

Monitoring of the engine condition implies ensuring that the engine stays within acceptable operating limits and taking corrective control action if these limits are approached or exceeded. These limits include overtemperature, overpressure, overspeed, and surge. Monitoring of the control system condition includes sensing the health of controller, sensors, and actuator components, and taking corrective action when a component failure is detected.

SYSTEM PERFORMANCE REQUIREMENTS

The control system will be designed to control the engine to minimize SFC or maximize thrust while maintaining safe, surge-free operation. Additional modes, such as engine life conserving, increased surge margin, and self trim may be required as pilot selectable modes.

Starting

The system will be capable of initiating a start anywhere in the starting envelope. The control functions during starting will include providing the proper light-off fuel flow, providing the fuel flow necessary to traverse the start region, and limiting fuel to ensure that critical engine operating limits are not violated (i.e., turbine blade temperature, turbine outlet temperature, surge, etc.) during the start. Also, geometries will be positioned as required for starting. Under certain conditions the starting system will be able to perform an air start without starter assistance.

Auto Reignition

The controller will sense a rapid decrease of compressor discharge pressure and initiate reignition if the rate of change of pressure is beyond a specified limit. The controller will distinguish between blowout and surge.

Steady-State Operation

Based on a PLA input and sensed engine parameters, the control system will provide for desired steady-state engine operation within a prescribed stability tolerance while observing critical engine parameter limits.

For any other than maximum power setting the control system will control the engine geometry, cooling, and fuel flow to operate the engine within 5% of the optimized minimum SFC except when operating on one of the engine limits.

When operating at the maximum power setting, the controller will cause the engine to develop within 5% of its maximum capable thrust while observing the following constraints imposed by engine speed, airflow, and temperature limits:

- The relationship between thrust and power lever should be linear within ±2% without discontinuities.

- Stabilized thrust at any power lever position should be repeatable within 2%.

- o For increases or decreases in PLA, engine thrust must be a monotonically increasing or decreasing function respectively.
- o Idle thrust should not exceed 2% of minimum aircraft landing weight.
- o Under steady-state operating conditions, engine thrust fluctuations between idle and maximum continuous thrust must not exceed $\pm$1% of intermediate thrust or $\pm$5% of the thrust available at the power lever position and flight condition, whichever is less.

The control system will be capable of holding a desired steady state operating point to within $\pm$0.2% corrected rotor speed.

The control system will observe steady-state operating limits* with respect to certain critical engine parameters. These limits will be as follows:

- o CDT
- o turbine outlet gas temperature
- o turbine rotor inlet gas temperature
- o turbine blade metal temperature
- o aft metal temperature
- o compressor discharge total pressure
- o mechanical rotor speed

Furthermore the controller will not allow steady-state operation above the corrected rotor speed (rotor speed corrected for design inlet temperature) limit. The control will also observe both a maximum and minimum inlet airflow, which is computed as a function of aircraft Mach number and the aircraft inlet characteristics. The engine control system will interact with the inlet control to minimize this constraint.

Finally, the control will provide the necessary compressor geometry control to provide 10% surge margin during snap accelerations and decelerations throughout the entire engine operating envelope specified. The minimum steady-state surge margin will be 20%.

Transient Operation

The control will be capable of allowing transient engine operation consistent with MIL-E-5007D including a 6-sec transition time capability from an idle PLA setting to 98% maximum power. The following transient goals (not requirements) should be met if they do not sacrifice stability or significantly increase control complexity:

- o idle to MIL (military or maximum thrust): 4 sec
- o 15% intermediate rated power (IRP) to MIL: 3.3 sec
- o 35% IRP to MIL: 2.2 sec
- o At 15% IRP a 10% thrust change should be achieved in 0.6 sec
  a 5% thrust change should be achieved in 0.3 sec
- o At 35% IRP a 5% change should be achieved in 0.25 sec
  a 10% change should be achieved in 0.30 sec
  a 15% change should be achieved in 0.50 sec

*Limit values omitted to avoid classification.

The above goals are for standard static sea level conditions and specify the time required to achieve 95% of the thrust change. Stable steady-state values should be achieved in an additional 10 sec. Additional assumptions are no customer bleed, no anti-ice, and no customer horsepower extraction. The MILE-5007D will be used to extrapolate the above goals to other flight conditions. Included are an additional 7 sec for the idle to intermediate response for conditions above 10,000 ft and a 25% increase in response time for nonstandard day, customer bleeds, horsepower extraction, and inlet distortion.

The control will observe certain limits in transitioning from one steady-state operating point to another:

- The control will not allow more than 50°F overshoot above the maximum CDT limit. The excursion above the maximum temperature will be limited to 0.5 sec.

- The control will not allow more than 60°F overshoot above the specified steady-state turbine outlet gas temperature limit. Transient temperature excursions above the steady-state limit will be no greater than 0.5 sec in duration.

- The control will not allow more than 60°F overshoot above the specified steady-state turbine rotor inlet gas temperature limit. Transient temperature excursions above the steady-state limit will be no greater than 0.5 sec in duration.

- The control will not allow more than 20°R overshoot above the specified steady-state turbine blade metal temperature limit.

- The control will not allow more than 10 psia overshoot above the steady-state compressor discharge pressure limit.

- The control will not allow operation with less than 10% compressor surge margin during transient operation.

- The control will not allow overshoots greater than 2.5% above the mechanical rotor speed limit. Furthermore, for nonstandard day inlet conditions, this overshoot will not be greater than 2.5% of the corrected rotor speed limit.

- As a goal, there should not be any undershoot on thrust, speed, or temperature on a deceleration to idle.

- During engine transients, the variation of engine airflow from the corresponding steady-state values of the power setting selected must not cause propulsion system instability.

Performance Requirements under Engine Variations

The typical variations due to build tolerances and deterioration of performance are summarized as follows:

Parameter	Variation	
Compressor efficiency	+2%	-2%
Compressor flow	+1%	-3%
Compressor pressure ratio	+4%	-4%
Turbine efficiency	+2%	-2%
Turbine flow	+2%	-1%
Burner pressure drop	+1%	-1%

The control will maintain the required thrust with no more than a 5% variation for the engine variations listed except when constrained by the engine protection limits and stability margins listed.

VI. TRADE STUDIES

Trade studies have been completed in several areas. These studies were necessary to more accurately define the digital controller and its associated interfaces. The following trade studies were conducted under Task I and are summarized in this report:

1. Flow Measurement Accuracy
2. Backup Control
3. Actuator Feedback Sensors
4. Torquemotor Driver

In addition, the following study was completed in the NASA digital components program (NAS3-22046) and is summarized here:

5. Fuel System Configuration

FLOW MEASUREMENT ACCURACY

A measurement of airflow is desired to predict thrust, conform with inlet constraints, avoid compressor surge, compute the fuel to air ratio for the fuel splitter, and estimate rotor inlet temperature. The first three items require the compressor inlet air flow while the last two items require the inclusion of selected bleeds. Consequently, both compressor inlet and exit flow measurements were considered.

Two basic methods of airflow measurement were compared. One computes the airflow from measurements of total pressure, static pressure, and temperature. The other uses the differential between total and static pressure, the static pressure, and temperature. Both calculate the airflow from the equation for the isentropic flow of a perfect gas.

The Flow Measurement Accuracy trade study examines the sensitivity of these two methods to measurement errors. Airflow equations to calculate the inlet weight airflow in terms of either total and static pressures or differential and static pressures were determined. Measurement error coefficients were obtained by taking the partial derivatives of airflow with respect to area, temperature, and pressure. These error coefficients were evaluated at eight different inlet conditions. A total estimate of the airflow error was obtained by multiplying the coefficients by assumed measurement errors and combining the results in a root-sum-square fashion.

For the purpose of evaluating the error in total airflow calculation, the following measurement errors were assumed:

$\delta A/A = 0.01$
$\delta T = 10°R$
$\delta P_T/P_T = 0.004$
$\delta P/P = 0.004$
$\delta \Delta P/\ P = 0.01$

Flow error sensitivity to measurement errors was computed using the following varients of the isentropic gas equation:

$$W = \frac{2.056\ AP}{\sqrt{T}} \sqrt{\left(\frac{P_T}{P}\right)^{\frac{2}{7}} - 1}$$

(for total pressure)

and

$$W = \frac{2.056\ AP}{\sqrt{T}} \sqrt{\left(1 + \frac{\Delta P}{P}\right)^{\frac{2}{7}} - 1}$$

(for differential pressure)

Compressor Inlet

Compressor inlet conditions were used along with the above measurement errors to calculate the entries in Tables 7 and 8. Table 7 contains the airflow errors contributed by total and static pressure measurements. Table 8 contains the errors contributed if differential and static measurements are used. The errors due to effective area and temperature errors have been entered in both tables. The root-sum square of the four contributing errors has been included for each inlet condition. If all the errors are normally distributed, statistically independent, and of nearly equal amplitude, approximately 92% of the errors will lie within the RSS value. The percentage of error in airflow is also calculated.

Table 7.
Flow measurement errors with total and static pressures.

N-- %	Alt-- ft	M_N	Flow error contributions $\frac{\partial W}{\partial A} \cdot \delta A$	$\frac{\partial W}{\partial T} \cdot \delta T$	$\frac{\partial W}{\partial P_T} \cdot \delta P_T$	$\frac{\partial W}{\partial P} \cdot \delta P$	Flow errors δW(RSS) --lb/sec	$\delta W/W$ --%
100	SL	0	1.54	-1.50	2.10	-1.49	3.35	
79.5	SL	0	0.98	-0.96	3.73	-3.35	5.20	
100	SL	1.2	2.20	-2.20	6.79	-5.63	9.35	
92.3	SL	1.2	2.38	-1.80	8.22	-7.23	11.35	CLASSIFIED
100	10000	1.2	2.10	-1.80	4.52	-3.66	6.44	
92.3	10000	1.2	1.75	-1.40	5.65	-4.95	7.84	
100	36089	0.9	0.70	-0.84	0.82	-0.53	1.47	
100	50000	2.0	0.91	-0.67	2.48	-2.11	3.45	

Table 8.
Flow measurement errors with differential and static pressures.

N-- %	Alt-- ft	M_N	Flow error contributions $\frac{\partial W}{\partial A} \cdot \delta A$	$\frac{\partial W}{\partial T} \cdot \delta T$	$\frac{\partial W}{\partial P} \cdot \delta P$	$\frac{\partial W}{\partial P} \cdot \delta P$	Flow errors δW(RSS) --lb/sec	$\delta W/W$ --%
100	SL	0	1.54	-1.50	0.72	0.32	2.29	CLASSIFIED
79	SL	0	0.98	-0.96	0.48	0.20	1.47	
100	SL	1.2	2.20	-2.20	1.36	0.58	3.44	
92.3	SL	1.2	2.38	-1.80	1.18	0.49	3.25	
100	10000	1.2	2.10	-1.80	1.03	0.44	2.98	
92	10000	1.2	1.75	-1.40	0.86	0.36	2.43	
100	36089	0.9	0.70	-0.84	0.34	0.15	1.15	
100	50000	2.0	0.91	-0.67	0.45	0.19	1.23	

A significant reduction in total flow error was achieved by using a differential pressure measurement. This reduction was obtained even though a higher percentage of error was used for the differential pressure measurement than for the total pressure measurement. Note that with the differential pressure measurement method the effective area becomes the significant contributor to flow area. Any increase in error in effective area above the assumed 1% will substantially increase the error in airflow.

In conclusion, the differential pressure measurement method is significantly more accurate for determining airflow than the total pressure measurement method.

Compressor Exit

The inlet flow estimate could be adjusted to account for bleed air, cooling air, and leakage. Alternatively, the pressure and temperature at the compressor discharge can be used to calculate an estimate of airflow. The latter method was investigated. The equations presented above for the inlet airflow from inlet pressure and temperature measurement are also appropriate for calculating compressor discharge flow.

Tables 9 and 10 present estimated compressor exit airflow error. A significant error reduction is again evident for the differential pressure flow measurement.

Table 9.
Flow measurement errors with total and static pressures.

N--%	Alt--ft	M_N	Flow error contributions: $\frac{\partial W}{\partial A}\cdot\delta A$	$\frac{\partial W}{\partial T}\cdot\delta T$	$\frac{\partial W}{\partial P_T}\cdot\delta P_T$	$\frac{\partial W}{\partial P}\cdot\delta P$	Flow errors: δW(RSS) --lb/sec	$\delta W/W$ --%
100	SL	0	1.24	-0.51	2.60	-2.11	3.61	CLASSIFIED
79.5	SL	0	0.87	-0.42	1.26	-0.91	1.83	
100	SL	1.2	2.31	-0.82	4.23	-3.30	5.90	
92.3	SL	1.2	2.06	-0.72	3.26	-2.43	4.61	
100	10000	1.2	1.74	-0.63	3.88	-3.19	5.35	
90.3	10000	1.2	1.51	-0.60	2.39	-1.79	3.40	
100	36089	0.9	0.59	-0.23	1.22	-0.98	1.69	
100	50000	2.0	0.73	-0.25	1.51	-1.22	2.09	

Table 10.
Flow measurement errors with differential and static pressures.

N--%	Alt--ft	M_N	Flow error contributions: $\frac{\partial W}{\partial A}\cdot\delta A$	$\frac{\partial W}{\partial T}\cdot\delta T$	$\frac{\partial W}{\partial P}\cdot\delta P$	$\frac{\partial W}{\partial P}\cdot\delta P$	Flow errors: δW(RSS) --lb/sec	$\delta W/W$ --%
100	SL	0	1.24	-0.51	0.62	0.25	1.50	CLASSIFIED
79.5	SL	0	0.87	-0.42	0.43	0.18	1.07	
100	SL	1.2	2.31	-0.82	1.14	0.46	2.74	
92.3	SL	1.2	2.06	-0.72	0.99	0.44	2.44	
100	10000	1.2	1.74	-0.63	0.86	0.35	2.07	
90.3	10000	1.2	1.51	-0.60	0.74	0.30	1.81	
100	36089	0.9	0.59	-0.23	0.29	0.12	0.71	
100	50000	2.0	0.73	-0.25	0.37	0.15	0.87	

BACKUP CONTROL

The requirement for a backup control is safety mandated and assumes particular importance with reference to digital electronic primary controls, due to the lack of in-flight control experience. This study sought to define a preliminary GMA400 backup control to meet this requirement. Particular areas investigated included determination of the minimal control variable set, proper failsafe positions for noncontrolled variables, necessary control logic and hardware to switch to and operate the backup controller, and probable backup control mechanization schemes. The control logic design was then validated against the GMA400 digital transient engine model for performance and stability.

The backup control logic was designed. Critical control variables were defined through failure analysis; these are the fuel flow and the compressor vane position. Failsafe fixed positions were determined for the remaining control variables: exhaust nozzle area (A8) = 25% open, turbine nozzle area (HPT) = 43% open, Bleed 1 = 13/15 open, and Bleed 2 = 14/15 open. These positions will be set as the null current position for the planocentric

actuators and solenoids involved. The resulting configuration is identical to a fixed geometry turbojet with variable compressor vanes. Required engine measured inputs are spool speed (N_H), inlet pressure (P_1) and temperature (T_1), compressor discharge pressure (P_3), and pilot command or PLA.

The digital transient engine simulation was exercised with the backup control changes in place. The results were quite good in terms of performance and compliance with engine limits. This verified the preliminary backup control logic design. Additional logic, including rate limits during switchover to and from the backup control, were not investigated with the simulation.

Analysis was begun to determine the control mechanization scheme using the GE report, "Backup Control for a Variable Cycle Engine" (AFAPL-TR-77-92) as a baseline. The selection of the backup configuration is dependent upon the airframe configuration. For a strictly "fly-by-wire" configuration that requires an electrical interface between PLA and the backup control, a dual digital channel approach is best. This is based upon (1) the close ratings between the duplicate digital and hydromechanical backup in the GE Study, (2) the evaluation from dissimilar to similar digital control for backup on the Hamilton Standard digital electronics reliability study, and (3) the requirement for an electrical interface to the backup control.

However, if a mechanical linkage exists between the PLA and the backup control, a hydromechanical backup control hookup in parallel with the primary control becomes the chosen configuration. In this case a transfer valve is also required to switch over the fuel flow and the compressor vane control from the primary. The major advantage of this hydromechanical backup control is survivability in the face of an electrical failure (i.e., lightning strike).

ACTUATOR FEEDBACK

A trade study was performed by Bendix to evaluate the selection of sensors for closing position loops through the digital controller. Sensors considered were devices that have demonstrated the capability to operate in the environment of an engine mounted fuel control. Three types of sensors were considered:

- resolvers
- linear variable differential transformers (LVDT)
- rotary variable differential transformers (RVDT)

The excitation and conditioning circuitry associated with each type of sensor was also considered when evaluating sensor accuracy, reliability, cost, and weight.

Resolvers are preferred where accuracy is the primary consideration with the capability of achieving $\pm 0.4\%$ of full scale accuracy over a 90 degree rotation and a temperature range of -65°F to 450°F. This is approximately three times better than LVDTs and up to five times better than RVDTs over the typical fuel control temperature range.

The failure rate for resolvers based on 750,000 hr of engine operation is on the order of 15 failures per million hours. No similar field experience data for LVDTs and RVDTs was available so no direct comparisons could be made of device reliability. However, LVDTs and RVDTs do not have a coupling to the moving element, and it would be suspected that they would be more reliable than resolvers for that reason. Failure of the resolver rotor coupling is the primary failure mechanism of the resolver for which the field data exist. Resolvers are being developed that eliminate this coupling and should therefore have comparable failure rates as LVDTs and RVDTs.

In terms of system cost and weight, there are no significant differences between the resolver, LVDT, and RVDT.

TORQUEMOTOR DRIVERS

Torquemotors are used as actuator interface devices between the digital controller and hydromechanical systems (e.g., variable geometry). A Bendix evaluation of high versus low power torquemotor drivers was performed as an aid to determining impact on controller size and weight.

An evaluation of high versus low power electrical current drivers for the controller output indicates that high power drivers require an extra stage of amplification to reach the maximum design current over the full temperature range of the driven device. Roughly, high power drivers are required when the maximum current exceeds 100 to 150 mA. The impact of such a driver (500 to -250 mA) on the controller is a 1.25 in.^{2} increase in board area, approximately a 2 oz. increase in control weight and a proportionally larger amount of heat to be removed from the unit. Components are sized for the higher power requirements, and thus the driver reliability is not significantly different.

FUEL SYSTEM CONFIGURATION

Fuel system trade studies were performed for NASA Lewis Research Center and are reported in NAS3-22046. These studies are summarized here.

Six different candidate fuel systems were conceptually defined for comparative trade studies. Appendix A describes these systems. The metering valves that determine the amount of fuel going to the engine are controlled by an electrical input from the digital control. A constant pressure drop is maintained across the metering valves by a throttling valve in systems using a centrifugal pump. Where a variable speed drive gear pump is used, the pressure drop across the metering valve is maintained by controlling the speed of the pump with an electrical signal from the digital control.

The trade study report paid particular attention to control weight, fuel temperature rise, and control cost. Its conclusions follow:

- o A variable delivery discharge throttled centrifugal pump with a retracting vane starting element is the preferable pump configuration (minimal fuel temperature rise).

- o A single pump configuration is best except in certain flight safety considerations.

- o For dual entry systems (main-primary) either dual metering systems or a single metering system with a flow divider could be used.

It is important to note that from a digital controller standpoint, all six of the configurations studied required two controller output channels and two feedback input channels.

VII. SUMMARY

The objective of this program phase was to develop the specification for a digital controller. This controller would have sufficient computing and I/O capability to control a variable cycle (VCE) single-spool (e.g., GMA200 ATEGG) or two-spool (e.g., GMA200 JTDE) configuration. The GMA200 is intended for advanced tactical fighter (supersonic) applications. Provision has been made for seven controlled variables. These are two fuel flows, variable compressor and turbine geometry, two cooling bleed flows, and variable nozzle area.

A multivariable control logic structure has been selected. Power commands, mode, and ambient conditions are used to estimate the equilibrium operating point. These schedules will then be adjusted to match the engine characteristics using an adaptive control algorithm. "Optimal" paths between operating points will be computed by a "trajectory generator" module. A proportional regulator is designed to track small perturbations from this nominal path. Failure detection and accommodation will be provided by a fault tolerant filter to compensate for arbitrary sensor failures; engine protection logic is provided to coordinate transfer to a controller backup; and a failure accommodating actuator compensation module provides a high performance interface to the actuators.

The design concept for a digital controller capable of implementing this control logic was developed. This required a specification of the GMA200 fuel control system with particular emphasis on the controller interface. Trade studies were identified, and their impact on the control hardware was presented. These included actuator selection, fuel system selection, and airflow measurement techniques.

Timing and sizing studies were completed. This resulted in the selection of a bit-slice processor (an Am 2901) with 28K EPROM/RAM. No single microprocessor was identified that could perform the required control logic in a timely manner. Multilevel microprocessors were found to be more complex and to require more power and space than a bit-slice based processor. In addition, the bit-slice processor can be programmed to emulate an existing microprocessor (i.e., 9900) instruction set but with added special purpose multivariable control operations.

The EH-K2 digital controller is a fuel-cooled advanced technology unit. It consists of 11 printed circuit board modules and associated interconnect harness. These include a CPU module, analog and digital input modules, an output interface module, a memory module, four pressure sensor modules, a cold junction module, and a power converter module. A fiber optic crosstalk channel (both receiver and transmitter) is provided for communication with an optional backup controller.

APPENDIX A
FUEL SYSTEM CONFIGURATIONS

Six different candidate fuel systems were conceptually defined for comparative trade studies. These systems incorporate a centrifugal pump described previously in this report. Consideration was also given to variable drive speed gear pump schemes for comparative purposes. The following is a short description of each fuel system configuration as depicted schematically in Figure A-1.

Configuration 1 is composed of (1) a fuel pump that includes a fuel inlet inducer that keeps the main centrifugal element filled with fuel at all inlet pressure conditions, a retracting vane starting element that furnishes fuel from light-off to idle RPM, and a centrifugal element that furnishes fuel from idle RPM to max thrust conditions; (2) a metering valve control assembly that includes a pressure drop control assembly and throttle valve to match fuel pump output to engine total fuel requirements; and (3) a flow divider and drain valve assembly. The flow divider meters the amount of fuel to the main fuel nozzles (with the remainder of the total fuel flow directed to the pilot fuel nozzles) to maintain the desired fuel/air ratio for the main and pilot nozzles. It also incorporates a shutoff valve that prevents fuel from the pump/control assembly from passing into the combustion chamber, collecting there, and causing a hot start when the control metering valve is at the minimum flow setting. Its location near the fuel nozzles also minimizes manifold fill time during starts. When the shutoff valve is closed, the primary and main fuel nozzles are vented overboard via the nozzle manifolds and flow divider. The shutoff valve is activated open (manifold drains closed) at light-off during a start and activated closed (manifold drains open) during shutdown.

Configuration 2 is composed of (1) two centrifugal fuel pumps operating in parallel with a common inducer and a starting pump, (2) a separate metering valve control assembly for each pump, and (3) two shutoff valves that isolate the pumps from each other. The primary and main fuel nozzles are each supplied by a separate fuel pump and control assembly. The main fuel nozzle system is operated in conjunction with the primary system to achieve the desired total fuel flow while maintaining the required fuel/air ratio at each set of nozzles. When the main system is not operating at low fuel demand conditions, its shutoff valve is closed. Likewise, if a failure should occur in the primary system, it can be isolated from the main system by closing its shutoff valve.

Configuration 3 is composed of (1) a single pump, including an inducer, starting element, and centrifugal element; (2) two metering valve control assemblies; and (3) two shutoff valves. The main system operates in conjunction with the primary system to achieve the desired total fuel flow while maintaining the proper fuel/air ratio at each nozzle. Its shutoff valve is activated open when the main fuel nozzles are flowing at the higher total fuel flows. The primary shutoff valve is used to isolate the primary metering valve control in case of failure.

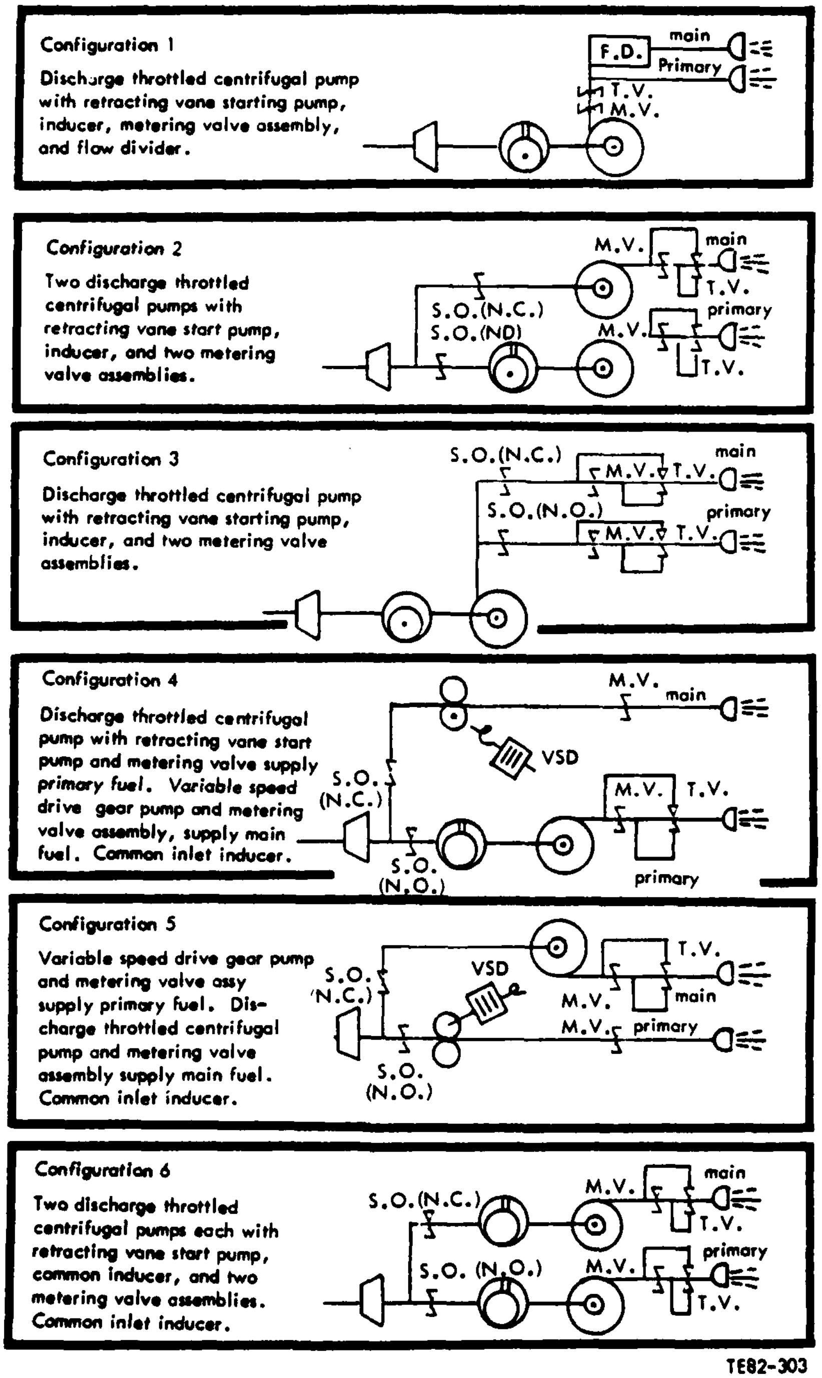

Figure A-1. Candidate fuel system schematic.

Configuration 4 is composed of (1) a primary system centrifugal pump and starting pump operating in parallel with a main system variable speed drive gear pump and a common inducer, (2) a separate metering valve control assembly for each pump, and (3) two shutoff valves that isolate the pumps from each other. The shutoff valves and metering valves are operated in the same manner as in Configuration 2.

Configuration 5 is composed of (1) a primary system variable speed drive gear pump operating in parallel with a main system centrifugal pump (no starting pump) and common inducer, (2) separate metering valves for each pump, and (3) two shutoff valves that isolate the pumps from each other.

Configuration 6 is essentially the same as Configuration 2 except that a retracting vane starting pump is added to the main fuel nozzles' pumping and metering system. The configuration has complete pump/control backup capability and means for making an air start in either primary or main systems with a nominal weight and cost increase over Configuration 2. This configuration evolved during the investigation of the "emergency operation" where it was observed that a slight modification to Configuration 2 would permit the aircraft to complete a mission after incurring any single fuel system failure (excluding gear box failures). Configuration 2 has individual pumps, metering valves, and shutoff valves for the primary and main nozzles. However, only the primary nozzle system has the starting pump since the main nozzles are turned on when a substantial flow already exists with the primary nozzles. Also, the two pumps share a common inducer. By putting a retracting vane starting pump in each nozzle fuel handling system, a single failure cannot make both nozzle systems inoperative at any condition. The burner can operate on a single set of nozzles (either set) up to 50% of the maximum total fuel flow with an undefined loss in efficiency.

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